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Jan Willem Storm van Leeuwen crunches the numbers and concludes that the cradle-to-grave CO2 emissions of nuclear power amount to 139-190 g CO2/kWh, the sum of contemporary emissions as well as latent emissions from waste management, decommissioning and mine rehabilitation.

Film review: Michael Moore's weird world of renewable energy haters

Jim Green – Nuclear Monitor editor

'Planet of the Humans' (POTH) has been watched by millions, and has attracted an extraordinary amount of commentary, since it was made freely available in April.[1]

The film is a full-frontal attack on renewable energy sources and the environment movement. Sure, not everything promoted as 'renewable' is indeed renewable, or sustainable, or socially equitable. And not everyone attaching themselves to the environment movement has environmental protection at heart. But any serious critique in *POTH* is lost in a fog of misinformation and overgeneralization.

Let's introduce the three anti-heroes responsible for this mess.

POTH executive producer Michael Moore needs no introduction, other than to note that he evidently knows very little about energy issues and appears to have been dragged along for the ride by his collaborators. "I assumed solar panels would last forever. I didn't know what went into the making of them," Moore told *Reuters*.[2] That's two good reasons why he shouldn't be making documentaries about energy issues.

Jeff Gibbs is writer, director, producer and narrator of the film. Gibbs worked on a number of Moore's previous projects – but in *POTH* he takes the lead. Gibbs insists that "everything you see in the film is accurate"[3] even as dozens of articles detail its many inaccuracies.[4-17] Joanne Doroshow, who worked as a researcher and fact-checker on a number of Moore's earlier projects, said that Gibbs was "someone we never let near the fact checking process" and "seemed attracted to conspiracy theories and information that was not factual".[18] She continued: "I cannot speak to what happened to Michael's films after I stopped helping to ensure their accuracy but it is excruciating to see what has happened now".

Ozzie Zehner, another *POTH* producer and an interviewee, is introduced in the film as a 'visiting scholar' at UC Berkeley and Northwestern University.[19] He ought to contribute some facts to counter Gibbs' conspiratorial muddle-headedness, but the two are as bad as each other. Zehner reminds me of Bjorn Lomborg – an opportunistic self-promoter using contrarianism to grab the spotlight. His 'critical environmentalism'[20] echoes Lomborg's 'skeptical environmentalism' and it echoes the 'death of environmentalism'[21] that introduced Michael Shellenberger to the world as a self-promoting contrarian.[22]

George Monbiot summarizes the film's problems:[10]

"The film does not deny climate science. But it promotes the discredited myths that deniers have used for years to justify their position. It claims that environmentalism is a self-seeking scam, doing immense harm to the living world while enriching a group of con artists. This has long been the most effective means by which denial – most of which has been funded by the fossil fuel industry – has been spread."

"Everyone hates a scammer. And yes, there are scammers. There are real issues and real conflicts to be explored in seeking to prevent the collapse of our life support systems. But they are handled so clumsily and incoherently by this film that watching it is like seeing someone start a drunken brawl over a spilled pint, then lamping his friends when they try to restrain him. It stumbles so blindly into toxic issues that Moore, former champion of the underdog, unwittingly aligns himself with white supremacists and the extreme right.

"Occasionally, the film lands a punch on the right nose. It is right to attack the burning of trees to make electricity. But when the film's presenter and director, Jeff Gibbs, claims, "I found only one environmental leader willing to reject biomass and biofuels", he can't have been looking very far. Some people have been speaking out against them ever since they became a serious proposition (since 2004 in my case). Almost every environmental leader I know opposes the burning of fresh materials to generate power. …

"The film offers only one concrete solution to our predicament: the most toxic of all possible answers. "We really have got to start dealing with the issue of population … without seeing some sort of major die-off in population, there's no turning back."

"Yes, population growth does contribute to the pressures on the natural world. But while the global population is rising by 1% a year, consumption, until the pandemic, was rising at a steady 3%. High consumption is concentrated in countries where population growth is low. Where population growth is highest, consumption tends to be extremely low. Almost all the growth in numbers is in poor countries largely inhabited by black and brown people. When wealthy people, such as Moore and Gibbs, point to this issue without the necessary caveats, they are saying, in effect, "it's not Us consuming, it's Them breeding." It's not hard to see why the far right loves this film.

"Population is where you go when you haven't thought your argument through. Population is where you go when you don't have the guts to face the structural, systemic causes of our predicament: inequality, oligarchic power, capitalism."

Even when the film-makers have a reasonable point to make, they mess it up. Promotional videos accompanying the film argue that people in the Global South should continue to develop their economies while those in developed countries need to sharply cut back. Fair enough, there's plenty of support among environmentalists for contraction-and-convergence approaches. But in *POTH*, the argument becomes so garbled as to be unrecognizable.

Likewise, the film-makers' argument that endless growth on a finite planet is impossible ought not be objectionable: it ought to be the starting point for any serious discussion about environmental sustainability. But in their clumsy hands, the argument trails off into muddle-headed, objectionable Malthusianism.

By all means discuss problems associated with renewables, but how on earth does this cryptic statement by Gibbs in *POTH* add to the sum of human knowledge: "It was becoming clear that what we have been calling green, renewable energy and industrial civilization are one and the same."

Gibbs ties the threads of his arguments together at the end of the film, but again it's a jumble: *"We humans must accept that infinite growth on a human planet is suicide. We must accept that our human presence is already far beyond sustainability and all that that implies. We must take control of our environmental movement and our future from billionaires and their permanent war on planet Earth. They are not our friends. Less must be the new more. And instead of climate change, we must at long last accept that it's not the carbon dioxide molecule that's destroying the planet, it's us. It's not one thing, but everything we humans are doing – a human-caused apocalypse. If we get ourselves under control, all things are possible, and if we don't …"*

Far-right supporters

The far-right are falling over themselves to promote the film.[23] "Left-wing greenies turn on Michael Moore. Give him a medal," a Murdoch tabloid columnist wrote, congratulating the film for "exposing the massive lies behind renewable energy".[24]

Breitbart described *POTH* as" the most powerful, brutally honest and important documentary" of Moore's career and argued that it could help get Trump re-elected by undermining proposals for a Green New Deal.[25]

Environmental journalist David Vetter wrote in *Forbes*:[5]

"Michael Moore … has defended the film, saying it is intended to be a warning about the involvement of corporate America in the environmental movement. But that isn't the message taken home by many who have watched it. Corporate fossil fuel-backed groups such as the libertarian Heartland Institute have boosted the film, and far-right politics blog Breitbart, backed by Trump backer and climate skeptic Robert Mercer, has said the film shows renewable energy is more polluting than fossil fuels. Far from taking a chunk out of corporate America, Planet of the Humans has been turned into a cudgel by big oil and the super rich."

Nuclear power

POTH doesn't discuss nuclear power, but that hasn't stopped nuclear advocates from endorsing the film's attack on renewables and using that as a launching pad for nuclear boosterism.[26-29]

Moore is friends with (and was mentored by) film-maker Robert Stone, who produced the wildly inaccurate pro-nuclear film *Pandora's Promise*.[30-31] They both spoke at a screening of *Pandora's Promise* in 2013, with Moore saying he hadn't made up his mind about nuclear power.[32]

POTH feels like a set-up. A pro-nuclear sequel to the anti-renewables film, perhaps? But there won't be a sequel. For starters, the film-makers couldn't find a distributor for *POTH* – that's why it was dumped on youtube. And in any case, the film-makers expressed skepticism and opposition to nuclear power in a recent online forum.[33]

Michael Shellenberger has enthusiastically promoted *POTH*, saying that it exposes "why renewables are worse for environment than fossil fuels"[34] and using the anti-renewables diatribe to promote nuclear power.[29]

Ted Nordhaus, a nuclear power advocate who collaborated with Shellenberger on the 'death of environmentalism' in the mid-2000s, criticized Shellenberger and some others for being "so single-mindedly pro-nuclear and anti-renewables that they have cheered the movie's cherry-picking, exaggerations, and conspiracies while largely excusing its deep Malthusianism."[35]

Shellenberger has become a favorite of the far-right and the climate science deniers. He was interviewed by Tucker Carlson on Fox TV last year, attacking renewables and in particular the 'green new deal'.[36] Recently Shellenberger was interviewed by Andrew Bolt – Australia's version of Tucker Carlson – to promote *POTH* and to promote nuclear power.[37]

Shellenberger's forthcoming book suggests his lurch to the anti-environment right is almost complete. The Harper Collins website provides this description of the book:[38]

"The risk of Earth warming to very high temperatures is increasingly unlikely thanks to slowing population growth and abundant natural gas. Curiously, the people who are the most alarmist about the problems also tend to oppose the obvious solutions. What's really behind the rise of apocalyptic environmentalism? There are powerful financial interests. There are desires for status and power. But most of all there is a desire among supposedly secular people for transcendence. This spiritual impulse can be natural and healthy. But in preaching fear without love, and guilt without redemption, the new religion is failing to satisfy our deepest psychological and existential needs."

So climate change isn't such a problem, and those who think it is should support nuclear power (and gas!) … but they don't for quasi-religious reasons. Where have we heard that before? That's right – from Carlson, Bolt and the rest of the far-right.

Zehner makes the case for fossil fuels in *POTH*, when discussing a solar power plant: "The whole thing is built using fossil fuel infrastructure … You use more fossil fuels to do this than you're getting benefit from. You would have been better off just burning the fossil fuels in the first place instead of playing pretend." But according to energy expert Assoc. Prof. Mark Diesendorf: "Solar panels generate the energy required to build themselves in 1–2 years of operation, depending on type of panel and location, and their lifetime is about 20 years; large wind turbines in 3–12 months, depending on size of turbines and location, and their lifetime is 25–30 years."[11]

Contradicting themselves

One last observation about this weird world of renewable energy haters – their extraordinary ability to turn on a dime and to contradict themselves. Jeff Gibbs said in an interview: "We don't attack any environmental leaders."[39] But in *POTH* he says: "Environmentalists are no longer resisting those with the profit motive, but collaborating with them. The merger of environmentalism and capitalism is now complete." And this: "What are they [environmental leaders] hiding and why are they hiding it? Is it their ignorance, or is it something else? What if they themselves had become misguided? What if they had made some kind of deal they shouldn't have made and are leading us all of the cliff?"

Shannon Osaka noted in *Grist* that the second half of *POTH* is "a jumbled and garbled set of conspiracy theories relating to the Koch brothers, the Sierra Club, Al Gore, and other prominent environmentalists."[40]

Gibbs said in an interview that he doesn't believe in or argue for population control of any kind.[39] But in *POTH* he says: "The reason we're not talking about overpopulation … is that would be bad for business." A handful of interviewees make similar comments, all of them handling a complicated topic with the subtlety of a sledgehammer.

Shellenberger told Tucker Carlson last year that one of the reasons people oppose nuclear power is that "they associate it with the bomb, which is wrong, they are two separate technologies."[36] But in 2018 Shellenberger argued that "having a weapons option is often the most important factor in a state pursuing peaceful nuclear energy" and that "at least 20 nations sought nuclear power at least in part to give themselves the option of creating a nuclear weapon".[41]

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Mom, Michael Moore & Me

Peter Sinclair

Following the release of the steaming dogpile of a movie, 'Planet of the Humans'[1], a lot of people have been surprised to hear the details of Michael Moore's reputational *harakiri*.

Have to say, I was not. But you see, I knew Michael Moore before he was, you know, Michael Moore.

There's been a barrage of criticism of the film, much of it simply pointing out gross factual errors[2], anachronisms[3], and boneheaded omissions[4].

But, perhaps especially in light of the embrace the film has gotten from the fossil fuel lobby[5], the climate denial media machine[6], and the white supremacist right wing[7], Moore felt he had to puff his environmental credentials in a recent op ed:[8]

"I founded the Huron Alliance, a Flint-based anti-nuclear group. We organized massive demonstrations to block the building of the Dow Nuclear plant in Midland, Michigan. Remarkably we were successful in its cancellation."

Well, actually, that's something I know a bit about, since I grew up in Midland, Michigan where I still live today, about 60 miles north of Flint.

There never was a "Dow Nuclear Plant"; however there was a project begun by the state's biggest utility, Consumers Power, back in the late 60s – for a large, dual unit-reactor, sited inside the city limits.[9]

It was my mother, Mary Sinclair, who raised questions about that plant, followed through on the hearing process, and pursued issues of nuclear safety and economics over almost 20 years, eventually profiled by *60 Minutes* on CBS in 1985, in a story titled 'Mary & Goliath'.[10]

And actually, it wasn't Moore, or any sign-carrying hippies, that got the plant cancelled, nor was it anti-nuclear efforts at all, but rather the same economic and technical contradictions[11] that are still killing nuclear plants today.[12]

Mom had technical chops honed as a researcher at the Library of Congress, where she had clearance to read and abstract classified Atomic Energy Commission (AEC) documents. She heard about the prospect of a new nuclear plant, knew there were issues, and started asking some questions. That lead to hearings, debates, and small-town acrimony shocking in its intensity.[13]

Ten years before Michael Moore showed up, it was my parents who got the midnight death threats, my Dad who had an attempt on his life, and his business almost destroyed, and my brothers and sisters who bore the brunt of being environmental pariahs in a small company town. CBS got the broad outlines right in the *60 Minutes* story.[10]

I was a teenager fascinated with the whole scientific and legal process, and spent as much time as possible making copies and getting coffee for attorneys, scientists, regulators, and engineers.

In June of 1971, the Xeroxed and hand-bound copy of *Nucleonics Week*, which was our coffee table reading, carried a story that there had been a series of failures at the AEC's Idaho test facility. The system that failed was a scale model of the emergency core cooling system (ECCS) that was then being built into nuclear plants all over the country.[14]

Not clear why they waited until dozens of power plants were already well along in the construction process to test the most critical safety system, but there it is.[15]

We knew what this meant. The ultimate accident at a nuclear plant is what Fukushima experienced in 2011: cooling failure, core melt, and devastating explosion. Although the "defense in depth" safety philosophy assured us that the massive containment buildings would be the final safety defense against such an explosion – that was, as we now know, a false hope. At Fukushima, those reinforced concrete barriers evaporated like tissue paper in the devastating hydrogen explosions that rocked the complex.

In our otherwise very much 'Leave it to Beaver' household, that kind of nightmare is what we talked about at the dinner table.

We also imagined a time in the future when irresponsible, unstable countries developed nuclear weapons from "peaceful" nuclear programs. And when weapons-grade materials being produced in large quantities might be coveted by terrorist organizations.

In short, the time that we live in now.

AEC hearings

To deal with the ECCS safety issue, the AEC scheduled hearings in Washington, in Summer 1972, in hopes of tamping down concerns, and cobbling together some kind of one-size-fits-all patch for the critical system.

The hearings brought nuclear construction to a halt all over the country, and nuclear critics got the blame for ballooning costs – a now-familiar feature[16] of nuclear projects worldwide.[17]

I sat in on portions of that hearing, as well as many others over some years, from Michigan to Chicago, all the way to the US Supreme Court.

Eventually, this and a series of self-inflicted construction snafus led Dow Chemical, Consumers' major customer for the plant's power and industrial steam, to file suit against the utility. In addition, other major industrial customers, GM, Ford, and Chrysler among them, joined in opposition to the expected massive rate increases that the crippled plant would lay on all ratepayers.

Concurrently, the OPEC oil embargo, and subsequent energy price jumps, caused a whole lot of companies to suddenly figure out they could do a lot more with efficiency than they ever thought possible. For example, between 1973 and 1975, Dow cut its energy use by 50 percent per pound of product. The postwar era of relentlessly increasing electricity demand was over.[18]

By 1977 or so, those in the loop knew that the nuclear industry was essentially dead in the water as investors had fled, and utilities were already looking at the first wave of bankruptcies and re-organizations that would rock the industry through the 1980s.

When Pennsylvania's Three Mile Island plant had its major malfunction, on March 28, 1979, the nuclear industry itself already in meltdown. Just a week before, Jane Fonda's and Jack Lemmon's movie 'The China syndrome'[19] had profiled a fictional accident scenario that came eerily close to reality.

In the movie, a scientist tells Fonda's character that an explosion at the plant "could render an area the size of the state of Pennsylvania permanently uninhabitable." The resulting wall-to-wall media frenzy included a memorable *SNL* skit with Dan Akroyd in a deadly Jimmy Carter send up.

A Michael Moore production, starring Michael Moore

For several months prior, Michael Moore had become a semi-regular guest at my parent's home. He was running an alternative paper, *The Flint Voice*, that had begun to cover the plant controversy, and was in the process of organizing demonstrations around the issue. Mom was happy to get any kind of media coverage, and Moore had it. There had already been a small demonstration of 70 or 80 people, and now there were plans for a larger one.

Three Mile Island threw gas on that fire, and Moore recognized the opportunity.

A month later, about 5,000 people showed up in Midland for a march, and Michael's organization was in control.

The idea was to gather at Revere Park, walk down Main Street to the plant site, and then speeches and entertainment.

Apparently a decision had been made that this was a Michael Moore production, starring Michael Moore. The program was designed to entirely focus on Michael, and a few selected friends, and not to allow local activists to speak, including Mary Sinclair, who many in the crowd were expecting to hear from.

Mary Sinclair, with some of the garbage that regularly turned up on her family's lawn.

When this suddenly became clear, I got very direct, loud, and profane with Moore about the obvious travesty, and members of the crowd overheard. They surrounded Mom, and lifted her to the hood of a car, where she spoke briefly to cheers.

The march followed, and then Moore put on a performance that was, in retrospect, sadly and completely characteristic. After waiting a dozen years for a moment when legitimate economic and safety concerns could be raised by a credible voice, when it was finally clear that there was an important conversation to be had, and when there was an opportunity for hundreds of local residents (many of whom were relatives and former family friends) to understand that concerns about our energy future were not just affectations for antisocial, scruffy, left-wing hippies, Mike stepped up to the podium and delivered to the crowd, and local media, exactly that: F-bombs, middle fingers to news choppers overhead, insults to the city and those that lived in it, and plenty of camera footage proving the stereotype for the evening news.

In the months that followed, what most people remember as the "anti-nuclear movement," the one with rock stars, Hollywood celebrities, and more demonstrations, played out.

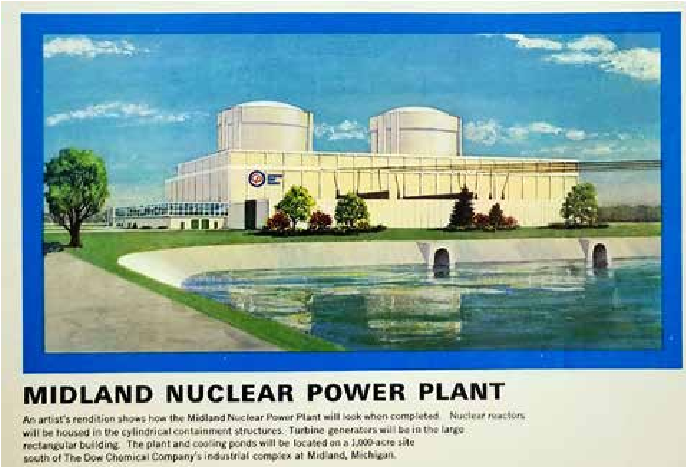
But the industry had been moribund for years already.

The Midland units, it turned out, were very much a genetic twin of Three Mile Island, and the accident brought major design flaws to light that required extremely expensive correction. Costs soared again, and five long years later, the project ground to a halt.[20]

Now Moore claims credit for stopping a nuclear plant, but the truth is, demonstrations didn't do it. F-bombs, signs and middle fingers didn't do it. Flawed designs, botched construction, market forces, and a business model inadequate to the changing times killed the Midland plant and a dozen other projects of that generation.

When Ronald Reagan took office in 1980, he removed the solar panels that Jimmy Carter had installed on the White House roof, and radically cut back research funding for renewable energy in favor of renewed emphasis on fossil fuels, oil, gas, and coal. An opportunity to change direction was lost.

Now, when we have a moment in history when we not only have the technology to take decisive action, we are confronted, perhaps, with the very last moment in which that action can make a difference and Moore has decided to make common cause with the greediest, most corrupt, most venal, most destructive industries that have ever existed.[21]



I'll let others judge for themselves why, but like I said, no surprise here.

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The SMR 'hype cycle' hits a hurdle in Australia

Jim Green – Nuclear Monitor editor

Dr. Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, writes about the small modular reactor (SMR) 'hype cycle' which shares many features with the hype that drove the 'nuclear renaissance' – the short-lived upsurge of interest in large reactors in the late 2000s.[1]

Cooper identifies three stages of the hype cycle:

1. Vendors produce low-cost estimates.
2. Advocates offer theoretical explanations as to why the new nuclear technology will be cost competitive.
3. Government authorities then bless the estimates by funding studies from friendly academics.

But the circular, self-referential SMR hype cycle has been disrupted in Australia by two government agencies, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Energy Market Operator (AEMO). The latest *GenCost* report produced by the two agencies estimates a construction cost of A$16,000 (US$10,700) per kilowatt (kW) for SMRs.[2]

The estimate has been furiously attacked by, amongst others, conservative politicians[3] involved in a federal nuclear inquiry last year, and the Bright New World (BNW) lobby group[3-5] which accepts secret donations from the nuclear industry and has a long history of spreading pro-nuclear misinformation.[6]

BNW objects to CSIRO/AEMO basing their SMR cost estimate on a "hypothetical reactor".[4] But BNW does exactly the same, ignoring real-world cost estimates for SMRs under construction or in operation. BNW starts with the estimate of US company NuScale Power, and adds a 50% 'loading' in recognition of past examples of nuclear reactor cost overruns. Thus BNW's estimate for SMR construction costs is A$9,132 (US$6,090) per kW.[5]

Two big problems: the NuScale cost estimate is bollocks, and BNW's proposed 50% loading doesn't fit the recent pattern of nuclear costs increasing by far greater amounts.

NuScale's construction cost estimate of US$4,200 per kW[7] is implausible. It is far lower than Lazard's latest estimate of US$6,900–12,200 per kW for large reactors[8] and far lower than the lowest estimate (US$12,300 per kW) of the cost of the two Vogtle AP1000 reactors under construction in Georgia (the only reactors under construction in the US).[9] NuScale's estimate (per kW) is just one-third of the cost of the Vogtle plant – despite the unavoidable diseconomies of scale with SMRs and despite the fact that every independent assessment concludes that SMRs will be more expensive to build (per kW) than large reactors.[10] Further, modular factory-line production techniques were trialled with the twin AP1000 Westinghouse reactor project in South Carolina – a project that was abandoned after the expenditure of at least US$9 billion, bankrupting Westinghouse.[11]

Lazard estimates a levelised cost of US$118–192 per megawatt-hour (MWh) for electricity from large nuclear plants.[8] NuScale estimates a cost of US$65 per MWh for power from its first plant.[12] Thus NuScale claims its electricity will be 2–3 times cheaper than that from large nuclear plants, which is implausible. And even if NuScale achieved its cost estimate, it would still be higher than Lazard's figures for wind power (US$28–54) and utility-scale solar (US$32–44).

BNW claims that the CSIRO/AEMO levelised cost estimate of A$251–330 per MWh for SMRs is an "extreme overestimate".[3] But an analysis by WSP / Parsons Brinckerhoff, prepared for the SA Nuclear Fuel Cycle Royal Commission, estimated a cost of A$225 per MWh for a reactor based on the NuScale design.[13] Power from the Russian floating plant – the only operational SMR in the world – costs an estimated US$200 per MWh (A$300 per MWh).[14] Thus the CSIRO/AEMO figure of A$251–$330 per MWh is reasonable while BNW's figure – A$123–128 per MWh with the potential to fall as low as A$60[3] – is an extreme underestimate.

BNW promotes[4] a 2016 study by Lovering, Yip and Nordhouse in support of its claims about nuclear construction costs – but the 2016 study was widely criticized[15] for cherry-picking, with one such critic being a former World Nuclear Association executive.[16] BNW also promotes[4] the US Energy Innovation Reform Project report[17], but the cost figures used in the report are nothing more than the optimistic estimates of companies hoping to get 'advanced' reactor designs off the ground. And BNW promotes the report by the Economic and Finance Working Group of the Canadian government-industry 'SMR Roadmap' initiative.[18] But the first-of-a-kind SMR cost estimates in the Canadian report – the most relevant being an estimated C$163 (A$177) per MWh for a 300-MW on-grid SMR – are all higher than BNW's estimate of A$123–128 per MWh.

Cost overruns

BNW proposes adding a 50% 'loading' to NuScale's cost estimate in recognition of past examples of cost overruns. Here are just some of the recent examples of much greater cost increases:

* The estimated cost of the high-temperature gas-cooled SMR (HTGR) under construction in China has nearly doubled.[19]

* The cost of Russia's floating SMR quadrupled.[20]

* The estimated cost of Argentina's SMR has increased 22–fold above early, speculative estimates.[21] and the cost increased by 66% from 2014, when construction began, to 2017.

* The cost estimate for the Vogtle project in US state of Georgia (two AP1000 reactors) has doubled to more than US$13.5 billion per reactor and will increase further.[9] In 2006, Westinghouse said it could build an AP1000 reactor for as little as US1.4 billion[22] – 10 times lower than the current estimate for Vogtle.

* The estimated cost of about €12.4 billion[23-24] for the only reactor under construction in France is 3.8 times greater than the original €3.3 billion estimate.

* The estimated cost of about €11 billion[25] for the only reactor under construction in Finland is 3.7 times greater than the original €3 billion estimate.

* The estimated combined cost of the two EPR reactors under construction in the UK, including finance costs, is £26.7 billion (the EU's 2014 estimate of £24.5 billion[26] plus a £2.2 billion increase announced in July 2017[27]). In the mid-2000s, the estimated construction cost for one EPR reactor in the UK was £2 billion[28], almost seven times lower than the current estimate.

Timelines

BNW notes that timelines for deployment and construction are "extremely material" in terms of the application of learning rates to capital expenditure.[5] BNW objects to the CSIRO/AEMO estimate of five years for construction of an SMR and proposes a "more probable" three-year estimate as well as an assumption that NuScale's first reactor will begin generating power in 2026 even though construction has not yet begun.[4]

None of the real-world evidence supports BNW's arguments:

* The construction period for the only operational SMR, Russia's floating plant, was 12.5 years.[29]

* Argentina's CAREM SMR was conceived in the 1980s, construction began in 2014, the 2017 start-up date was missed and subsequent start-up dates were missed.[30] If the current schedule for a 2023 start-up[31] is met it will be a nine-year construction project rather than the three years proposed by BNW for construction of an SMR. Last year, work on the CAREM SMR was suspended, with Techint Engineering & Construction asking Argentina's National Atomic Energy Commission to take urgent measures to mitigate the project's serious financial breakdown.[32] In April 2020, Argentina's energy minister announced that work on CAREM would resume.[33]

* Construction of China's HTGR SMR began in 2012[34], the 2017 start-up date was missed[35], and if the targeted late-2020 start-up is met it will be an eight-year construction project.

* NuScale Power has been trying to progress its SMR ambitions for over a decade and hasn't yet begun construction of a single prototype reactor.[36]

* The large reactors under construction in the US are 5.5 years behind schedule and those under construction in France and Finland are 10 years behind schedule.

* In 2007, EDF was boasting that Britons would be using electricity from an EPR reactor at Hinkley Point to cook their Christmas turkeys in December 2017 – but construction didn't even begin until December 2018.[37]

Learning rates

In response to relentless attacks from far-right politicians and lobby groups such as BNW, the latest CSIRO/AEMO *GenCost* report makes the heroic assumption that SMR costs will fall from A$16,000 per kW to A$7,000 per kW in the 2030s. The report states that SMRs were assigned a "higher learning rate (more consistent with an emerging technology) rather than being included in a broad nuclear category, with a low learning rate consistent with more mature large scale nuclear."

But there's no empirical basis, nor any logical basis, for the learning rate assumed in the report. The cost reduction assumes that large numbers of SMRs will be built, and that costs will come down as efficiencies are found, production capacity is scaled up, etc.

Large numbers of SMRs being built? Not according to expert opinion. A 2017 Lloyd's Register report[38] was based on the insights of almost 600 professionals and experts from utilities, distributors, operators and equipment manufacturers, who predicted that SMRs have a "low likelihood of eventual take-up, and will have a minimal impact when they do arrive".[39] A 2014 report produced by *Nuclear Energy Insider*, drawing on interviews with more than 50 "leading specialists and decision makers", noted a "pervasive sense of pessimism" about the future of SMRs.[40] Last year, the North American Project Director for *Nuclear Energy Insider* said that there "is unprecedented growth in companies proposing design alternatives for the future of nuclear, but precious little progress in terms of market-ready solutions."[41]

Will costs come down in the unlikely event that SMRs are built in significant numbers? For large nuclear reactors, the experience has been either a very slow learning rate with modest cost decreases, or a negative learning rate.[42]

Real-world data

Obviously, the starting point for any logical discussion about SMR costs would be the cost of operational SMRs – ignored by CSIRO/AEMO and by lobbyists such as BNW.

There is just one operational SMR plant, Russia's floating plant. Its estimated cost is US$740 million for a 70 MW plant.[20] That equates to A$15,900 per kW – almost identical to the CSIRO/AEMO estimate of A$16,000 per kW. Over the course of construction, the cost quadrupled[20] and a 2016 OECD Nuclear Energy Agency report said that electricity produced by the Russian floating plant is expected to cost about US$200 per MWh with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure.[14]

Figures on costs of SMRs under construction should also be considered – they are far more useful than company estimates, which invariably prove to be highly optimistic.

The World Nuclear Association states that the cost of China's HTGR is US$6,000 per kW.[43] Costs are reported to have nearly doubled, with increases arising from higher material and component costs, increases in labour costs, and increased costs associated with project delays.[19]

The CAREM SMR under construction in Argentina illustrates the gap between SMR rhetoric and reality. In 2004, when the reactor was in the planning stage, Argentina's Bariloche Atomic Center estimated an overnight cost of USS$1,000 per kW for an integrated 300-MW plant (while acknowledging that to achieve such a cost would be a "very difficult task").[44] When construction began in 2014, the cost estimate was US$15,400 per KW[45] By April 2017, the cost estimate had increased US$21,900 per kW.[46]

To the best of my knowledge, no other figures on SMR construction costs are publicly available. So the figures are:

A$15,900 per kW for Russia's light-water floating SMR

A$9,000 per kW for China's HTGR

A$32,800 per kW for Argentina's light-water SMR

The average of those figures is A$19,200 per kW, which is considerably higher than the CSIRO/AEMO figure of A$16,000 per kW and more than double the BNW estimate of A$9,132 per kW.

SMR hype cyclists going around in circles

The hype cycle partly explains the growth of nuclear power a half-century ago, and the short-lived resurgence 10–15 years ago.[1] Currently, SMR hype cyclists are practiced and polished and they have an endless amount of propaganda to recycle and regurgitate. But their economic claims are sharply contradicted by real-world data. And the coordinated propaganda campaign simply isn't working – government funding and private-sector funding is pitiful when measured against the investments required to build SMR prototypes let alone fleets of SMRs and the infrastructure that would allow for mass production of SMR components.

Wherever you look, there's nothing to justify the high hopes and hype of SMR hype cyclists. Argentina's SMR program is a joke. Plans for 18 additional HTGRs at the same site as the demonstration plant in China have been "dropped" according to the World Nuclear Association.[47] Russia planned to have seven floating nuclear power plants by 2015, but only recently began operation of its first plant.[29] South Korea won't build any of its domestically-designed SMART SMRs in South Korea – "this is not practical or economic" according to the World Nuclear Association[48] – and plans to establish an export market for SMART SMRs depend on a wing and a prayer … and on Saudi oil money which is currently in short supply.[49]

Mark Cooper argues that rather than learning from past experience, nuclear hype cyclists are becoming even more deluded:[1]

"Has the nuclear industry been cured of its myopia? Not at all. In fact, there is a sense that the disease is getting worse, not better, since the characteristics that are said to make small modular technologies attractive are precisely the characteristics that make other alternatives more attractive. In the past, the refusal to look at alternatives could be explained by the fact that the advocates were looking at different characteristics – claiming that huge baseload facilities are indispensable. They dismissed the alternatives because they are too small or too variable.

"Today, they emphasize small size and speed to market, characteristics on which the alternatives are vastly superior. At the same time they ignore the innovation that has sharply increased renewable load factors and the dramatic advances in information and control technologies that have improved the ability to forecast and integrate renewables."

Cooper's analysis is reflected in the latest CSIRO/AEMO report, which finds that SMR construction costs per kW are 2–8 times higher than costs for wind or solar.[2] Costs per unit of energy produced are 2–3 times greater for nuclear compared to wind or solar including either two hours of battery storage or six hours of pumped hydro energy storage.

Likewise, the latest Lazard's report on levelized costs of energy shows that nuclear power is more expensive than renewables:[8]

Energy Source	*Cost / MWh*
Nuclear	US$118–192
Wind power	US$28–54
Solar PV utility scale	US$32–44
Solar thermal with storage	US$126–156
Geothermal	US$69–112

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CO2 emissions of nuclear power: the whole picture

Jan Willem Storm van Leeuwen

'Nuclear power is a clean means to generate electricity. At least, it causes no CO2 emissions.' Based on this view some environmental activists became proponents of nuclear power, for fear of the disastrous consequences of climate change. At first glance they seem to be right: nuclear power stations are silent, clean and (usually) operate reliably day and night, summer and winter. But alas, also in this case it's no free lunch. Nuclear power causes CO2 emissions indeed, and at a growing rate.

In a nuclear reactor enriched uranium is being fissioned, releasing heat. The heat is converted into electricity by means of steam turbines. Enriched uranium, the fuel for the nuclear reactor, is produced from uranium ore by means of a sequence of industrial processes. Uranium ore is recovered from the earth's crust at several places in the world.

When a certain portion of the uranium has been fissioned, the nuclear fuel has to be removed from the reactor, because the fuel is not suitable anymore for energy production. About once every year the spent fuel has to be replaced by fresh nuclear fuel. The question arises: what happens with the spent nuclear fuel?

Process chain

The technical system aimed at generating electricity from uranium has three components:

1. Upstream processes: needed to produce nuclear fuel from uranium ore in the earth's crust.
2. Mid-section: construction and operation of the nuclear power plant.
3. Downstream processes: needed for safe disposal of all radioactive wastes generated during the operational life of the nuclear power plant.

The three-component structure of a process chain – upstream processes, mid-section and downstream processes – is also valid for fossil-fueled power stations, actually for nearly all production processes.

Upstream part of the nuclear process chain

The upstream processes comprise the recovery of uranium from the earth's crust, transport, refining and conversion into a gaseous uranium compound, enrichment and fabrication of fuel elements that can be placed into the nuclear reactor. Without these upstream processes nuclear power would be impossible. Without nuclear power these processes would not exist. Each process consumes energy (electricity and fossil fuels) and emits CO2 into the atmosphere. Especially the recovery of uranium from the earth's crust consumes large amounts of fossil fuels and produces much CO2.

The average uranium content of the globally exploited ores decreases as more ore is mined, due to the fact that the easiest accessible and richest available ores are mined firstly. The richest ores offer the highest return on investment for the mining companies. The lower the uranium content, the more rock has to be mined and chemically treated and the more energy is consumed to extract one kilogram of uranium. Below a certain ore grade, the recovery of 1 kg uranium consumes as much energy as can be generated from 1 kg uranium in a nuclear power plant. This phenomenon is called the energy cliff of uranium ore. This conclusion is based on a physical analysis of data published by uranium mining companies during many years.

Construction

Construction of a modern nuclear power plant consumes about 850,000 tons of concrete and about 150,000 tons of steel, plus thousands of tons of other materials. The production of these construction materials and of the equipment of the plant consumes a lot of energy, accompanied by substantial CO2 emissions. The construction activities themselves contribute also to the CO2 emissions.

Operation, maintenance and refurbishments

The nuclear reactor is the sole component of the nuclear process chain that does not emit CO2. This fact may be the source of the incorrect view that nuclear power would be CO2 free. All other processes of the nuclear system, without which a nuclear power plant cannot produce electricity, do emit CO2.

During the fission process in the reactor, the radioactivity of the nuclear fuel and the surrounding materials increase a billion-fold. This increase is caused by the generation of fission products and activation products. Activation is the phenomenon that non-radioactive materials, such as concrete and steel, become radioactive by irradiation by neutrons from the fission process. It is impossible to artificially reduce the radioactivity of a material, or to make it less harmful. Radioactivity is harmful to all living organisms.

Numerous radioactive components of the power plant have to be replaced one or more times during the operational lifetime of the plant. In the end the reactor vessel may be one of the few original components that are not replaced. Operation, maintenance and refurbishments of a nuclear power plant consume considerable amounts of energy and emit CO2.

Downstream part of the nuclear process chain

An old Latin verb says: 'In cauda venenum', in the tail is the venom. This verb might apply to nuclear power. Due to the generation of large amounts of human-made radioactivity the spent nuclear fuel is strongly radioactive and remains so for long periods. The specific activity of spent fuel decreases with time due to natural decay of the radionuclides. After 1,000 years the specific activity of spent fuel is still a million times higher than the lethal level for human beings. An operating nuclear power plant generates each year an amount of artificial radioactivity corresponding to more than 1000 times the amount that is released by the explosion of one nuclear bomb of 15 kilotons (Hiroshima bomb).

The largest part of the human-made radioactivity is retained in the spent fuel elements at the moment of discharge from the reactor. In addition, a considerable amount of radioactivity is dispersed in thousands of tons of construction materials. These materials are released at the decommissioning and dismantling of the nuclear power plant after closedown. What should happen with these radioactive materials?

During the past decades various concepts have been proposed for definitive disposal of radioactive materials. According to the nuclear industry the radioactive waste issue is not a problem. However, a fact is that after 70 years of civil nuclear power, all human-made radioactive materials are still stored at vulnerable temporary storage facilities.

The sole way to prevent more dispersal of radioactive materials into the human environment is to isolate the materials from the biosphere for periods of hundreds of thousands of years. There are designs of definitive disposal facilities in galleries deep in geologically stable formations. Nowhere on earth is such a geologic repository operational for high-level nuclear wastes. Sweden and Finland are the farthest with the construction of geologic repositories for spent fuel and for other radioactive wastes. Construction of a geologic repository and sequestering the radioactive wastes are energy-intensive and produce large amounts of CO2.

Another important part of the downstream processes is the decommissioning and dismantling of the nuclear power plant at the end of its operational lifetime. Globally some 600 nuclear power plants are to be dismantled some day. The mass of radioactive debris and scrap released from one nuclear power station may amount to some 100,000 tons at various levels of radioactivity. The radioactivity is caused by neutron irradiation and contamination with radionuclides during the operational life of the plant. Some 10,000 tons are expected to be classified as high-level waste.

In addition, many thousands of cubic meters of contaminated soil are to be considered radioactive waste, due to leaks and small accidents. First estimates of dismantling nuclear power plants in the UK and in Switzerland point to a cost as high as the construction cost, or even higher. It is not clear if these estimates include cleanup of the plant site and final disposal of the radioactive debris and scrap.

According to the nuclear industry, dismantling should occur many decades after final shutdown and will take a period of at least 10 years. How much energy and human effort will be needed? Who will pay these activities some 60–100 years after final shutdown?

No new technology is needed to adequately finish the downstream processes. Geologic repositories are similar to deep underground mines. Energy consumption and CO2 emissions of other downstream processes can reliably be estimated based on similar industrial processes without radioactive materials. Energy consumption and CO2 emission of all downstream processes together prove to be about as large as those of the upstream processes including construction and operation of the nuclear power plant.

Contemporary CO2 emissions and latent CO2 emissions of nuclear power

The CO2 emissions of the upstream processes, construction and operation are called the contemporary CO2 emissions, because they occur before and during the operation of the nuclear power plant. By means of a physical analysis of all processes and activities separately it is possible to reliably estimate the contemporary CO2 emission of nuclear power. The methodology was developed during the 1970s and 1980s and has been peer reviewed extensively by international peer groups. The used data originate exclusively from the nuclear industry. The model nuclear power plant in this analysis corresponds with the newest nuclear power plants presently operating. The assumed lifetime electricity production is higher than the current global average. Energy consumption and CO2 emission of uranium mining plus milling is calculated based on data published by the mining industry.

The CO2 emission of the downstream processes, that is inextricably coupled to the present application of nuclear power, will occur in the future, long after closure of the nuclear power plant. For that reason these postponed emissions are called the latent CO2 emissions of nuclear power. The latent emissions are hidden in the future and are usually not taken into account.

A physical analysis of the complete nuclear process chain comes to estimates of the contemporary CO2 emission of 65–116 grams CO2 per kilowatt-hour delivered electricity, and of the latent emission of 74 g CO2/kWh. The spread of the figures of the contemporary emissions is caused by differences of the presently operational uranium mines. The differences result from different properties of the mined uranium ore, such as the ore grade and the chemical composition of the ore. The CO2 emissions of the uranium mining plus milling increase as more ore is mined, because the richest ores are mined first, so the remaining ores are leaner.

Table 1. Contemporary CO2 emissions of nuclear power

PROCESS	g CO2/kWh
uranium mining + milling, low, rich ores	7.1
average	32.3
high, lean ores	57.4
refining + conversion	2.8
enichment (ultracentrifuge)	2.6
conversion + fuel element fabrication, including zircalloy production	3.4
construction of the nuclear power plant	24.9
operation + maintenance + refurbishments of the power plant	24.4
sum emissions of contemporary processes – low	*65*
average	*90*
high	*116*

Table 2. Latent (future) CO2 emissions of nuclear power

PROCESS	**g CO2/kWh**
definitive isolation of the radioactive waste of the upstream processes	14,0
conversion and definitive isolation of depleted uranium	5.7
dismantling of the nuclear power plant, inclusief definitive isolation of the debris	40.9
interim storage and definitive isolation of the spent fuel	8.2
rehabilitation of a proportional part of the uranium mine	4.8
sum emissions of future processes	*74*

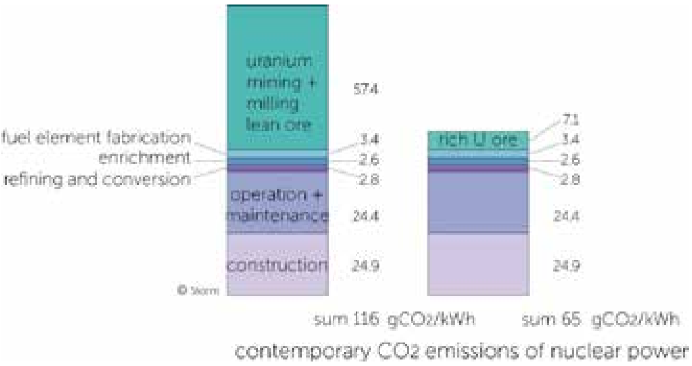

Figure 1: Contemporary CO2 emissions of nuclear power

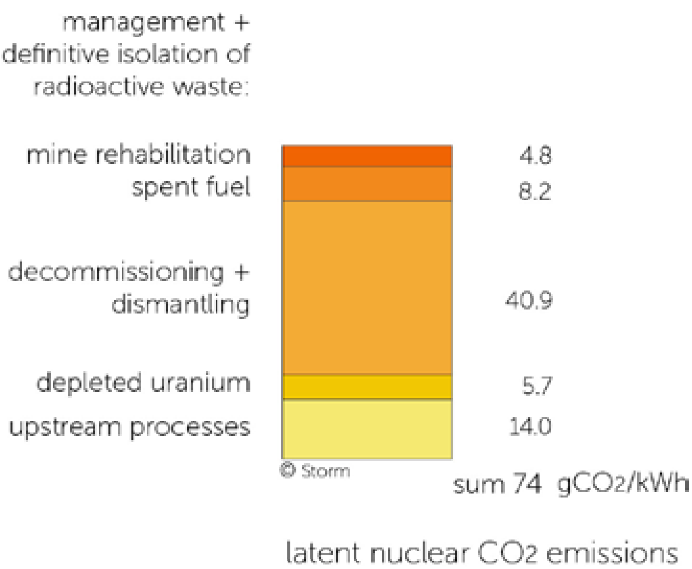

Figure 2: Latent CO2 emissions of nuclear power

CO2 trap of nuclear power

To keep the global nuclear capacity constant at the present level, about 370 GWe, each year until 2060 nine new nuclear power plants should be connected to the grid. The present construction rate is far lower than nine plants a year for a period of 40 years. During the coming four decades nearly all currently operating nuclear power plants would reach the end of their technical lifetime and have to be closed down.

Assumed that the global nuclear capacity would remain constant, the average CO2 emissions of nuclear power would become higher than 400 g CO2/kWh after the year 2070. With this figure nuclear power comes into the same emission range as fossil fuelled power stations. This phenomenon is called the CO2 trap of nuclear power. The chance is dim of discovery of major new rich uranium ore deposits, by which the CO2 trap could be postponed to a later year. During the past four decades no such deposits have been discovered, despite extensive exploration.

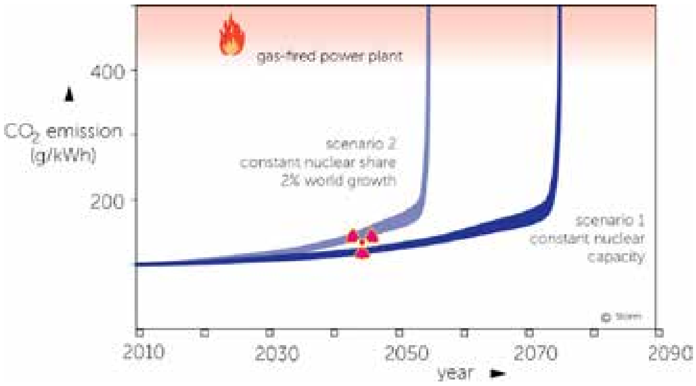

Figure 3: The nuclear CO2 emissions are rising with time, because the richest uranium ores get depleted and the available ores become leaner. Consequently the energy investments for recovery of uranium from the crust are rising with time. During the past 3-4 decades no new large rich uranium deposits have been discovered.

Visibility of upstream and downstream activities

The downstream processes of the nuclear energy system are usually invisible to the public, because they occur at other places far from the nuclear power plant, often on different continents. Moreover, large time differences may play a part: downstream processes can be invisible because they have not yet taken place.

These facts may contribute to the incorrect view that a nuclear power plant is a stand-alone system, and consequently that for calculation of the CO2 emissions of nuclear power only the power plant itself has to be taken into account. Usually construction, operation and maintenance of the power plant are also left outside the scope. Actually the specific CO2 emissions of nuclear power is identical to the emissions of the whole cradle-to-grave sequence of processes that makes nuclear power generation possible.

Nuclear legacy

The downstream part of the nuclear chain involves a nuclear legacy for future generations. During the disasters of Chernobyl and Fukushima jointly an amount of artificial radioactivity has been globally dispersed about equal to the production of one nuclear power plant during one year. This amount corresponds with only 0.01% of the amount of human-made radioactivity that is temporarily stored within the biosphere at vulnerable temporary storage facilities. Further dispersion of the human-made radioactive materials will certainly occur,

potentially causing disasters that may dwarf Chernobyl and Fukushima, if man does not invest adequate amounts of energy and human effort to prevent that.
The Second Law of thermodynamics is relentless.

Prospects of nuclear power

In 2018, the global gross energy production of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%. From these figures it follows that globally the nuclear contribution to CO2 reductions is minor, even if nuclear power was free of CO2 emissions.

How are the prospects for nuclear power? The most advanced types of currently operational nuclear power plants cannot fission more than 0.5% of the uranium nuclei present in natural uranium as found in nature. Since the dawn of civil nuclear power in the 1950s, the nuclear industry is working on nuclear energy systems, based on a uranium-plutonium cycle, that would be able to fission 30-50% of the nuclei in natural uranium.

However, an operating nuclear power plant that could fulfil this promise has never been realized in practice. After seven decades of research in seven countries and investments of hundreds of billions of dollars, this type of nuclear power plant is fading off the scene. This failure can be explained by reason of technical problems and limitations arising from phenomena governed by the Second Law of thermodynamics.

Research on the use of thorium as a net energy source, based on a thorium-uranium cycle, started also in 1950s. Thorium is not fissionable and has to be converted into fissionable uranium in a nuclear reactor The technical problems and limitations arising from the Second Law of thermodynamics apply all the more so to nuclear power plants based on thorium. Development of thorium-based energy systems was halted during the 1970s.

From the above observations it follows that nuclear power in the future has to rely exclusively on the currently operational nuclear reactor technology.

Conclusions

The view that nuclear power is free of CO2 emissions turns out to be a fallacy, originating from disregarding construction, operation, maintenance, upstream processes and downstream processes of a nuclear power plant.

Actually, the specific CO2 emission of nuclear power is the same as the joint emission of all processes without which nuclear power would be impossible.

The cradle-to-grave CO2 emission of nuclear power is 139-190 g CO2/kWh, the sum of the contemporary emissions (65-116 g CO2/kWh) and the latent emissions (74 g CO2/kWh). These figures are the result of a comprehensive physical analysis of data on all involved processes published by the nuclear industry during the past years.

CO2 trap. The CO2 emission of nuclear power will rise in the future, due to depletion of rich uranium ores. If the world nuclear capacity would remain constant at the present level, the nuclear CO2 emission will surpass the emission of gas-fired power plants after the year 2070.

Nuclear legacy. The downstream processes of nuclear power plants must be performed in such an effective way that nuclear disasters will be prevented that may dwarf the disasters at Chernobyl and Fukushima.

Energy debt. The present use of nuclear power leaves behind a substantial energy debt for the future generations. It comprises the future energy investments required to complete the downstream processes adequately.

In 2018 the world energy supply of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%.

The most advanced types of nuclear power plants that are currently operational, or will become operational, cannot fission more than 0.5% of the uranium nuclei present in natural uranium.

Net energy production by reactor systems that, according to the nuclear industry, could fission 30-50% of the uranium nuclei in natural uranium proved to be infeasible.

Thorium-based nuclear power plants proved to be infeasible as well.

Failures of both the uranium-plutonium and the thorium-uranium systems can be attributed to phenomena governed by the Second Law of thermodynamics.

Also in the future nuclear power has to based solely on the present reactor technology.

Background documents

Descriptions of the processes, calculations, methodology and references to used publications can be found in the following reports which can be downloaded from www.stormsmith.nl/reports.html. It should be emphasized that all data used in this analysis originate from publications of the nuclear industry and associated official institutions and from uranium mining companies.

Global context and prospects of nuclear power
Uranium-plutonium breeder systems
Thorium for fission power
Contemporary CO2 emissions of advanced nuclear power
Decommissioning and dismantling
Methodology of energy analysis
Energy debt, latent CO2 emissions, latent entropy
Emission of non-CO2 greenhouse gases
Life-cycle nuclear CO2 emissions
Advanced reference reactor and EPR
Uranium mining + milling
Uranium for energy resources
Unconventional uranium resources
Uranium from seawater
Energy cliff and CO2 trap
Industrial views on radioactive waste
Geologic repositories and waste conditioning
Problems for the future – message to the future
Construction and OMR of nuclear power plants
Radioactive waste management – future CO2 emissions
Uranium mine rehabilitation