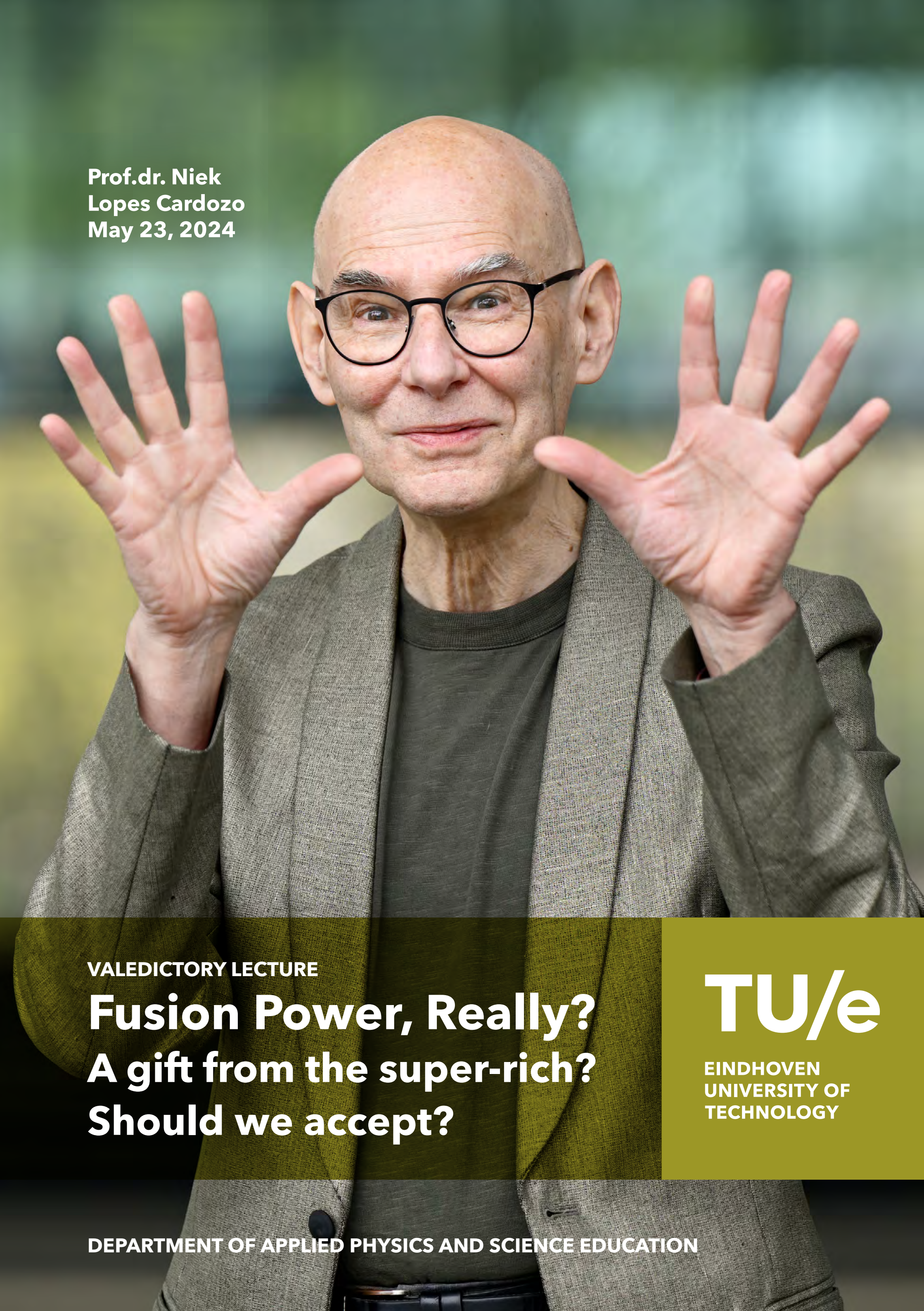
Fusion Power, Really?



Prof.dr. Niek
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May 23, 2024

VALEDICTORY LECTURE

Fusion Power, Really?
A gift from the super-rich?
Should we accept?

EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

DEPARTMENT OF APPLIED PHYSICS AND SCIENCE EDUCATION

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Introduction

Dear chair, dear colleagues, and former colleagues, dear students, friends, family and all who took the trouble of being here, in person or online, and who add meaning and shine to this gathering with your presence, it's a privilege to share this final hour of my life as a professor with you.

Can and will the super-rich accelerate fusion?

I had a strange dream last night in which I arrived at the Pearly Gates and somehow had a face-to-face with God. They asked if there was anything on my mind, anything at all, that was keeping me from finding peace and I said, "Well, I have spent my life pursuing fusion energy and people keep joking that it is always 30 years away, so please can you tell me: will it ever work?" And God scratched Their head and said: "Mwah…I don't know…maybe in 30 years?"

But God may not have factored in that mankind would distribute wealth in such a way that the 25 richest people own as much as the poorest half of the world population. These people are so rich that, if they wanted, they could just give fusion energy to the world. Solve the energy problem, once and for all. As a gift.

Or is that a false statement? Wasn't there a reason why mankind hasn't mastered fusion power yet? Something to do with tiny cross-sections, crazy high temperatures, inaccessible fuel and uncanny complexity? Surely, money does not trump the laws of nature. You can't purchase a perpetuum mobile for all the bitcoins in the world.

Clearly, scientific obstacles must be removed before industry can build a working fusion power plant. But suppose that we reach that point where scientists and engineers concur that the knowledge and technology base is sufficient to have a shot at a fusion demonstrator. Would it be conceivable that big venture capital could bring us fusion power soon? Speed up the technology development, similar to how SpaceX developed rockets quickly and efficiently?

AND DO WE WANT THEM TO?

And at the same time, we must query the other side of the proposition. Do we actually want fusion power? Is it really the miracle cure that the proponents make it out to be? If it isn't, should we accept it – even if it is a gift? Are we, facing the climate crisis, in the position to say *no, thanks* to a technology that could provide mankind with CO_2-free power? Even if we know it comes at a cost? And if we do want it, do we want it as a gift? Is there such a thing as a gift from the super-rich?

But I'm getting ahead of myself. Let me pedal back for a minute and spend a few words on what fusion power is, why we might want it in the first place, and how come we don't have it yet.

Back to basics: fusion works...

Nuclear fusion, the fusing of the nuclei of light atoms, powers the universe. It is the most effective way in which nature can transform mass into energy. It does so about ten million times more effectively than the chemical reactions involved in burning fossil fuel (yes, these convert mass into energy too). Hence, it needs very little fuel.

So, first of all: fusion works. There is not a shred of doubt about that. The physics is sorted.
Second: it is the one known and well-understood natural process that frees up energy and that has not yet been put to practical application.

...AND SMELLS OF ROSES

Which is surprising because it does have a rather wonderful poster: it does not emit CO_2 or any other harmful gas; it uses absurdly little fuel – just a few hundred kg per year for a large power plant; And it is safe – not because we make it safe but because it is safe in and of itself; and the parts of the reactor that become radioactive remain so for only 100 years or so. And it smells of roses.

At least, that is what you are led to believe if you visit the website of a fusion research institute or company. And that is why many people with no technical knowledge of fusion power think that it is a miracle cure for the energy hunger of mankind. And that is why it is up to us – scientists, engineers – to realize that potential and in the best possible way.

It is also why I decided to work in this field 43 years ago. And stayed.

"OF ALL THE LIES..."

Now, paraphrasing the baseball legend Yogi Berra – as famous for his aphorisms in the US as Johan Cruyff is here: "Of all the lies that I have just told you, half ain't even true." Or more accurately: most are half-true. Fusion energy is not nearly as wonderful as people would have you believe. I'll get to that in a bit.

But it does have rather great world-saving potential. It is one of the handful of energy sources we know of that could provide a meaningful fraction of the world's energy demand. And it really does not emit CO_2 and it really is very safe and there really is fuel for a very long time. Those claims are actually true. So, let's give it shot, shall we?

FUSION REACTIONS AREN'T HARD TO ACHIEVE...

Now, you'll probably think that making fusion reactions happen must be dauntingly difficult. Because why else is it taking so long to make fusion power available? Actually, it is not difficult at all. A child can do it, quite literally. There are plenty of reports of schoolkids who have constructed working fusion reactors in garages. These reactors are called 'fusors'. You can find building instructions on the internet. The principal components are stainless steel salad bowls from IKEA. Cost: € 6.99. It's a bestseller and has recently been lowered in price – no doubt because of the hype among underage fusion reactor builders.

Our students built one too. A very good one actually, possibly the best in the world. Slightly more advanced than the salad bowl contraption. Our 'TU/e Fusor' can produce tens of millions of fusion reactions per second and enough neutrons to necessitate serious shielding. But does it produce net energy? Not by a long shot. Those fusion reactions release a few microwatts, orders of magnitude less than the power needed to run the machine.

So, what is the catch? The fusion reactions have a high threshold energy, simply because the nuclei that must fuse each have a positive charge and therefore expel each other. This works out in such a way that the fuel 'burns' at a temperature of…150 million °C.

That is a high temperature indeed. But with the present state of science and technology, it is no longer a problem to achieve and sustain it.

...BUT NET ENERGY OUT IS

If 150 million °C is not a problem, then what is? Well, actually, the temperature *is* the problem. Not to achieve it, but it costs power to keep the fuel at that high temperature: heat loss. Therefore, we must reach the condition in which the burning fuel heats itself. And that requires a certain size of machine or very strong magnetic fields or very strong lasers. As in: the strongest, largest magnets or the strongest lasers ever constructed. And you have to master very complex physics: the stability of a hot plasma suspended in magnetic fields, the turbulence in such a plasma, its interaction with the vessel, etc.

That’s why it has taken so long.

But, as we’ll see, we have come to a point where all of this has been figured out, pretty much. The knowledge base is there. We believe that, with some confidence, we can build a working fusion power plant. That wasn’t the consensus ten years ago. Not at all.

On a personal note

If you'll allow me, I should like to share some personal history here. Ten years ago, I felt that fusion development wasn't going anywhere. Of course, researchers were doing interesting and high-quality work. In terms of understanding, of the ability to predict the performance of our plasma devices, progress was impressive. But the roadmap of the European program foresaw the operation of the large, international, proof-of-principle experiment ITER by 2035, to be followed by the construction of the first demonstrator DEMO, which could be expected to operate by 2060. And that is only the demonstrator. Commercial fusion would come at least a decade after that. And if the first batch turned out to be a success, it would still take more than 50 years to build the thousands of plants that are needed to make an impact. By then, we'd be well into the next century!

Frankly, I was losing heart. I was about to jump ship. I didn't see the program going anywhere.

A PIVOTAL MOMENT IN MY CAREER…

In autumn 2016, at the 70^{th} and final anniversary of the foundation FOM, of which I was the chairman at the time, I shared my frustration with Hans Chang, former director of FOM and the Royal Academy KNAW. He said, "Why don't we organize an international workshop in the Royal Academy with thought leaders from different fields of energy, including renewables as well as fission and fossil, to discuss the future of fusion?"

This workshop took place in May 2017. I'm still grateful to Hans, as well as to Wim van Saarloos – President of the Academy at the time – and Richard van de Sanden, who acted as chair of the workshop. Because that workshop helped me a lot in shaping my thoughts and getting the perspective straight.

In retrospect, this workshop took place at a pivotal moment in time, and not just for me.

I wrote an input paper in which I meted out why fusion was going to come too late and wouldn't be competitive to boot. A highly critical analysis in which I was not pulling my punches. Colleagues from the EU fusion community weren't happy at all.

A few surprising responses though. Many of the non-fusion participants, from renewables as well as fossil energy, said: "Of course, we want fusion. The energy transition won't be over by 2050 and fusion is the energy we want, eventually. No doubt about it."

I found that interesting because these people had little knowledge of fusion. But they did have a good general sense of the energy system and of the enormity of the required energy transition. And total faith that fusion energy would come one day. But not soon.

…AND IN THE HISTORY OF FUSION

Another interesting – in retrospect, very significant – thing happened. The director of the MIT nuclear science department participated in the workshop. He, Dennis Whyte, is a colleague from fusion research and a dear personal friend. Dennis and I have, several times, arrived at the same conclusions concerning fusion strategy via completely independent and different pathways.

So, before the workshop started, we had a chat over a coffee in Amsterdam and it turned out that he fully concurred with my analysis. He too didn't think that the ITER-DEMO route was going anywhere. Now, Dennis is a resourceful person, and one has to admire his response. He brought a group of PhD students together and said: "We are MIT, we are the best engineering school in the world" – yes, they say that at MIT, too – "and it cannot be that we aren't able to invent a fusion power plant that is smaller, smarter, cheaper, and *much* quicker to build than the ITER-DEMO roadmap." They did exactly that.

And then, and this was precisely at the time of the KNAW workshop and was very hush-hush then, he spoke to venture capitalists.

Now, here is a question to you.

A start-up company proposes building a machine with the same performance as ITER, where ITER is the world's flagship, 20-billion-euro fusion reactor. This start-up, only a handful of people, mostly quite young, claims to be able to build their machine within five years with a fraction of the budget. They are a bunch of PhD students with no experience in either building a device or running a business. And the basis of their design is a new, untested magnet technology. Would you believe their claim? Would you stake your own money?

Maybe not, huh?

Enter the super-rich

Now, if I told you that someone did back this company – and with two billion dollars, no less – would you find their claim more trustworthy? It does make a difference, doesn't it? Surely there must have been due diligence before that sort of money was plunged down?

In 2018, the company Commonwealth Fusion Systems (CFS) was founded. In 2021, it realized its first milestone, a 20 T superconducting magnet using high-temperature superconductors with initial funding, then acquired more than two billion dollars. Today, it is well underway with the construction of a compact fusion reactor that has performance specs very similar to ITER – which they intend to start operating in 2026. The project appears to be on schedule. CFS has been voted the most successful start-up in the US for several years running.

THE PRIVATE FUSION BOOM

This signaled the start of an unprecedented acceleration in fusion. Startups popped up like mushrooms and were backed by serious money. In the meantime, more than 50 start-ups emerged around the world, backed by more than seven billion private dollars.

The US is home to most of these start-ups, as you might have expected. But Europe is catching up, with a number of very respectable newly-formed companies, including a few in the Netherlands.

Now you'll ask, can I please show you the time schedules of the international ITER project and that of the CFS reactor side by side. And explain how it is credible that a start-up with just a few hundred people can be so much faster. Good question, and I'll attempt to answer that in a tick.

PROGRESS IN BASIC SCIENCE

But to give credit to the government programs, they too have been making good progress lately. And let there be no mistake – the projects of the start-ups are all founded on the knowledge base created by the publicly-funded research program. Nobody contests that. Let's therefore have a look at the strides of the basic science first.

The past few years have seen a barrage of press releases about scientific breakthroughs. Record upon record of fusion energy yields, highest temperatures, longest pulses. The European flagship experiment JET produced a world record fusion output power in 2022, which was followed later that year by the announcement by the US laser fusion lab NIF that they had achieved, for the first time ever, ignition and net energy output. Last December, NIF reported successful repeats of their breakthrough experiment – demonstrating that it hadn't been a lucky hit. And as recently as last February, JET came back with an improvement on their own fusion energy record.

And I hasten to add that it is not just the USA and Europe either. Other highlights were recently reported by South Korea (maintaining a temperature of 100 million °C for 40 seconds) and China (70 million °C for 17 minutes).

Now, before you lose your cool over this, NIF generated 3.2 MJ of fusion energy – that is the equivalent of a bar of chocolate. And JET released 69 MJ of fusion energy – worth about 70 cents if sold as heat, less if converted into electricity first. And even worse, the energy needed to run those experiments was still many times larger than the energy released.

But they are genuine scientific milestones – you could say that from here, the road to net energy generation is relatively clear.

THE START-UPS...

Back to the start-ups now. Over the past few years, several dozens of these have seen the light. And they are being backed by billions of dollars. A few words about these start-ups:

1. They are highly competent teams, laser-focused on realizing their targets. They recruit fusion specialists – such as our students – as well as engineers from other fields, professionals from industry with a track record of building things that work.
2. About half of them aim to realize a demonstrator fusion power plant. They use a great variety of approaches, from fairly conventional magnetic confinement machines – mostly with some clever twist – to exotic, way out-of-the-box concepts for which it is difficult to assess whether they have a chance of working or not.
3. Others focus on key technologies. Technologies that are likely to be useful for future power plants independently of the specific design. Plasma heating technology, measurement technology, advanced materials, fuel purification processes, remote handling, etc.
4. All of them expect that fusion power will hit the market within 10-15 years.

...AND THE INVESTORS

And a word about the investors that back these companies too. Are they indeed the super-rich? Initially, that was definitely a factor. Among others, CFS was supported by Bill Gates' Breakthrough Energy Ventures and (Vinod) Koshla Ventures. Another of the bigger start-ups, General Fusion, had Jeff Bezos among its principal investors. They were there right from the start and helped kick off the upsurge of fusion business.

But by now, many high-tech investment funds are buying into fusion. There is even a sense among them that fusion energy is a must-have. FOMO! And they use a portfolio management strategy – they buy into a selection of different fusion technologies. They don't pick a winner, they spread the risk. I'll show you in a minute why that is a smart strategy.

TOWARDS PUBLIC-PRIVATE PARTNERSHIPS

What's the response of governments to this development? Are they happy with those start-ups? I'd say, initially they were not. They accused start-ups of selling snake oil and even took one to court. But that attitude is changing rapidly. Now, the governments want to work with the private parties. You see the launch of public-private partnerships programs in the USA, in the UK, in China, in Japan, and most recently also in Germany.

THE RACE TO FUSION POWER IS ON

And we see competition between international players. The USA wants to get there faster than China and teams up with Japan; the UK wants to lead the world too; and Europe says, "Hang on, but we were the leaders in this field" and wants to keep that position.

So, the race is on. There is news every week and fusion has never been so exciting. But how much of this is real? And how much is just hype?

Why can private companies move so much faster?

I promised you a comparison of the time schedules of the ITER-DEMO line and that of start-ups, such as the MIT spin-out Commonwealth Fusion Systems (CFS). Whereas the ITER-DEMO program takes some 75 years from the decision to build ITER to the expected full operation of DEMO, CFS plans to cover that distance in 15 years. And this is just one example. Most fusion companies expect to launch a net energy-providing demonstrator within 10-15 years.

How can these companies expect to move so much quicker than the government programs? In my analysis, this can be understood if we realize that in the ITER-DEMO approach, the aim is to build the perfect, definitive machine the first time around. Performance, tritium generation, durability, long-term operation, all of it. Whereas the companies aim for a demonstrator that scores okay on performance while the expectations for long-term reliability, let alone life cycle issues, are much lower. Their demonstrator is not the definitive machine.

Rather, it is the first step in an evolution, which is the correct perspective. If we need thousands of fusion power plants to make the required impact, then surely the first tens, or even hundreds, are there mostly to learn how to build better ones!

By minimizing the build time, these companies do indeed 'plan for learning'. That is a crucial factor. It is much more important to design a development path that allows for efficient learning than to try and get everything right the first time.
By the way: the iconic JET experiment, recently closed but still the leading fusion experiment in the world for the past four decades, was built within five years – greenfield to start of operation too.

Another crucial factor is that, because of the short innovation cycle, these companies can absorb new technological developments from outside the field. Some use high-temperature superconducting magnets, a technology that was not available ten years ago and which has gotten an enormous boost precisely because several fusion companies have started to develop those magnets.

Some use advanced 3D printing of materials such as tungsten. And, of course, there is the advent of machine learning – AI, if you will – to explore the design space and find optimal configurations is an important factor. And so on…

Pick the winner or de-risk and accelerate?

So, should we pick one start-up and pool all our money to back them? Or should we rather have a whole lot of start-ups and develop many reactor concepts in parallel? What is a rational strategy here?

Well, imagine a situation where there are a whole bunch of companies – serious companies with competent teams – that are pursuing fusion energy via different routes. Some use magnets to confine the plasma, some use lasers, some use high currents, pistons, rail guns, etc. Now, if it was completely clear who was going to be the one that was much better than all the others, the choice would be simple: back the winner.

However, all these different concepts have pros and cons. One may have a problem that is completely circumvented by another, which may have yet another issue that is hard to crack. If it was easy, it would have already been done long ago. But it isn't easy, precisely because you can trade in one problem for another, but you can't avoid problems altogether. The truth is that in this complex field of options and problems, it is difficult to assess the probability that a particular approach will lead to success eventually.

But by trying many concepts at the same time, in parallel, the probability that at least one will succeed is surely much larger than that of a single trial. That probability will not exceed unity, of course, and even if you try all concepts, there is still the possibility that all will fail. But by trying many, you definitively reduce the risk of not getting there.

Now you'll say, "Yes, of course this is so, but it is also very expensive to try many concepts in parallel." True, but if you expect successful fusion to create value for society, then you should evaluate the upfront costs against the future value creation. It is an optimization problem, which is extra interesting when you are looking at rapid, exponential growth. Because in that case, you must also consider how many power plants you'll build in the first generation and the second, etc.

Scaling up too fast comes with financial risk; scaling up more slowly means that the revenues will come later and therefore be worth less due to discounting.

Sam Ward and I looked at this problem and found that the rational thing to do is to try some 5-10 different concepts in parallel. In practice, this means: develop all concepts that are being proposed.

I find it fascinating to see that the private investors – and now the government programs sponsoring public-private partnerships as well – do spread their money and appear to follow the strategy that is also indicated by our analysis.

Of all the lies that I've told you, half ain't even true

If you visit the websites of fusion establishments, you are likely to be fed one-liners, soundbites, black-and-white statements. "The surest path to limitless, clean, fusion energy" (CFS). "The future is fusion" (FIA). "… safe, sustainable and green electricity for future generations" (UKAEA). "Clean Energy. Everywhere. Forever." (General Fusion). "…clean, abundant and safe energy for all" (Proxima), etc. …

And if you want anything more than that, it very quickly becomes technical. The messaging then aims more at explaining – educating – than trying to give a balanced assessment.

I, too, find it very difficult to provide balanced information. On the one hand, I should like to convey hope, enthusiasm and trust and to stress the potential. On the other hand, I know that behind almost every word is a world of complexity and daunting challenges.

A complete assessment of pros and cons tends to be concise on pros, whereas the list of issues, challenges and difficulties is long and detailed. Before you know it, the pros are drowned in the sea of cons. And that wouldn't give a balanced picture either. However, leaving out cons would amount to lying by omission.

The reality is that the messaging is usually carefully crafted to suit the receiver, be that the general public, politicians or investors.

But there is one target group with whom we are brutally honest: students. After all, it is quite something to introduce young people to a field to which they may dedicate their career. So: brutal honesty there. So much so that students have often asked me if I could perhaps be a little less brutally honest. No, I won't. But I do thank our students for keeping us honest.

AN EXAMPLE OF MIXED MESSAGING: THE FUEL

I'll give you an example of the intricacy of correct messaging: the fuel narrative. As I said earlier, the fusion reaction needs extremely little fuel. Hence the soundbites: "limitless, abundant, forever…" Now I do have to become a little technical. The fuel used by a fusion reactor is lithium. A 1 GW power plant uses 100 kg per year. That is as much as the lithium in two Teslas. That plant generates perhaps a billion euros in revenues per year, so if needs be we can easily buy second-hand Teslas and take out the lithium. Hence: "limitless", etc.

True. But not true.

Because, while the reactor does indeed *consume* only 100 kg lithium per year, there is about 100 *tonnes* of it present in the reactor. Two *thousand* Teslas. Not so little then, but still okay. But what I haven't told you is that the lithium in the blanket is not just lithium but the lighter isotope lithum-6, which makes up only 7.5% of natural lithium. So now we really need more than a thousand tonnes of natural lithium – 30 thousand Teslas – for one power plant.

But how do we separate such quantities of ^{6}Li from the natural lithium? Long story short: the only process that is used on an industrial scale uses mercury. Now, mercury is a toxic heavy metal, the use of which the world is trying to cut down on. For the 100 tonnes of ^{6}Li for one power plant, we may need about ten thousand tonnes of mercury. That is five times the world's annual mercury production. This is not a process you'd want to scale up to provide thousands of fusion power plants with fuel. And to add that: the main source of mercury is China. In an increasingly polarized world, such a single origin dependency is highly unwanted.

So, you see…we started with a pretty innocent true statement about the use of lithium and now it turns out that behind that statement is a world of challenge. In this concerns the key selling points of fusion power: the abundance of fuel, the cleanliness of the technology, and its capability to provide energy sovereignty.

I'm not saying that the lithium issue cannot be solved. But it isn't solved at the moment, and as long as that is the situation, we are looking at a process that is environmentally hazardous, politically sensitive and not scalable.

I discussed this example to demonstrate that, if we are serious about the ‘fusion energy proposition’, it is our duty to look down the supply chain at processes, at substances, at their origins, at the ethics of those, at the mining of raw materials and at the ecological footprint.

At the very least, fusion researchers will then *know* that they are lying by omission *when* they are lying by omission.

Fusion power has world-saving potential, but it isn’t a silver bullet. And it doesn’t smell of roses either.

Upscaling – and ethics

And we should do so while being mindful of the required upscaling. We are not in this business to build one fusion power plant. We are in this business to help 'save the world', and for that we need ten thousand fusion power plants.

It is very much the same as with other energy technologies: scaling up by a factor of ten thousand changes the face of things. It is one thing to have wind parks here and there, but to fill the North Sea with wind parks is something else altogether. The risk and the waste of a single nuclear fission plant are easily managed; times ten thousand, it's a different proposition. And let's not forget: 100 years ago, fossil fuels were a local issue at best. But scale it up to present day intensity and it changes the face of the earth for good.

It really is that last factor of ten that makes all the difference.

THE ENERGY MIX: A MIX OF MORAL DILEMMAS

We, as energy scientists, often speak about 'the energy mix' as a mix of technologies with specs that can compete or complement and that should be chosen such that the most reliable and cheapest energy can be delivered to society.

But the energy mix isn't just that. It is also a mix of moral dilemmas, of different environmental impact profiles, different risk profiles, different ethical connotations, different emotional responses in the public. Different accessibility in different parts of the world too. And those aspects must be considered, too, when we envisage the energy mix. No energy source is perfect, and we must deal with the fact that the use of energy as we know it comes at a price.

We need to know and consider all these aspects because only then can we have a meaningful conversation about the question of whether we should accept the gift of fusion power.

My take on the present status of fusion energy

Is fusion energy coming? Yes, I believe that the feasibility will be demonstrated in the next decade.

Will it be a miracle cure? No, certainly not in the beginning. Fusion power plants will not be very efficient or clean or economical at market introduction, which is why it is so important to *plan for learning*. Fusion needs to become much better than the power plants that are presently on the drawing board.

Will fusion energy be scalable? The jury is still out on that. It is definitively necessary to spend research power and budget on reducing the raw materials needed for a fusion power plant and to critically assess the processes down the supply chain – the techno- and socioeconomics of fusion – because small issues times 10,000 become big issues.

Will the development of fusion power be accelerated by the start-ups and the role that industry is now taking? Yes. No doubt about it. And we see the combined effect of synergy and competition, the race between geopolitical entities. See what happened when vaccines for COVID needed to be developed and time was of the essence.

Should we accept fusion energy as a gift from the super-rich? Well, a gift from the rich, really? But generally, no, it shouldn't be a gift; we need to develop fusion in a public-private partnership. As the economist Mariana Mazzucato would say: we must not socialize the cost of development only to privatize the profits.

But the backing of start-ups by venture capitalists has definitely set things in motion.

Call to action

FOR THE NETHERLANDS…

And that brings me to the finale of my final lecture. Where does the Netherlands stand in this pivotal, hyper-dynamic moment in time? Are we in the back seat or are we driving?

With the realization of fusion power becoming a real prospect in the near future, this field is becoming ever more integrated: cross-disciplinary, integrating physics and engineering and social science; integrating academia, industry and government. And we need to work with the public, too, on the social license.

These are all things that the Netherlands is good at. And this is a great moment to step into the arena.

Just three weeks ago on May 3, we had the Dutch Fusion Day here in Eindhoven, organized jointly by DIFFER and the energy institute of TU/e, EIRES. We expected between 50 and 100 participants, but we had to close registration when the room was filled to capacity at 200, well-spread across academia, industry and government.

One of the conclusions of the day was that the Netherlands is well-positioned to present itself as the host country of the first European fusion power plant.

We have the infrastructure, the seaports, the connectivity. We have an energy-intensive economy, a large population and little space. We have a top-notch high-tech industry, a strong international network and many companies that are already involved in the ITER project or other fusion projects, as well as high-tech companies with superb capabilities. During the Dutch Fusion Day, the CTO of VDL, Gustaaf Savenije, said: “Don’t worry. If you can invent it, we can make it.” High time to capitalize on that capability.

…AND TU/E & DIFFER

DIFFER and TU/e are the center of the Dutch fusion knowledge network. And it is perhaps not stressed often enough that top researchers from multiple departments at TU/e are involved in fusion research: Electrical Engineering, Mathematics and Computer Science, Mechanical Engineering, Applied Physics, Industrial Engineering & Innovation Science. Dozens of researchers in all.

EIRES has recently opened a fusion office with the express purpose of building a national platform that brings industry and academia together.

We have the best fusion master's program in the world right here at TU/e. Uncontested.

We have an Honors Academy student team called Nuclear Fusion Power for the Netherlands, which is developing all of the *non-technical* roadmaps for the realization of a fusion power plant in the Netherlands. It takes the city and seaport of Rotterdam as a case study for the location of a fusion power plant, working closely with the foundation Rotterdam Reactor – which explores the same casus. Other obvious candidate locations could be the North of the Netherlands or Chemelot.

We have all that. And quoting Milena Roveda, CEO of the European consortium Gauss Fusion, who spoke at the Dutch Fusion Day: "Fusion needs more Dutchness". By which she meant boldness and a can-do mentality.

So, with no responsibilities left and only an ocean of holidays ahead of me, can I just say to all of you, colleagues, students, executives…

The future is in your hands – make fusion happen. And please, don't take 30 years!

Acknowledgements

43 years in national and international fusion research, in academia … it's been quite a journey. A journey made in good company, of many, many, people. I can mention just a few, and hope for the understanding of the hundreds that have also been very important for me. I should like to remember, thank, or greet:

My teachers and advisors, when I started as PhD student: prof Kees Braams, inspiring long-time leader of the Dutch fusion institute FOM, my promotor Hans de Kluiver, copromotor Cor Bobeldijk and Luuk Ornstein, all of whom are regretfully no longer with us.

During a postdoc period JET: my room and teammates Ben Tubbing and Theo Oyevaar.

Back at Rijnhuizen, the RTP-gang with Noud Oomens and Tony Donne as group leaders, under the inspirational leadership of Chris Schuller, and Marnix van der Wiel as institute director.

The late Frans Sluijter, who admirably smoothed out the somewhat bumpy process leading to my appointment as part-time professor at this university.

That was also the start of my role as academic promotor. A highly rewarding experience – and it is great to see that so many of the researchers I had the privilege of guiding went on to have a successful career, quite often in fusion – and sometimes somewhere else entirely, in industry, education, or even the arts. The mini-symposium earlier today was testimony of that.

I had a particularly interesting time directing the Dutch fusion programme, from 2000 on. Interesting, not easy, because we had to deal with severe budget cuts while, with the ITER project becoming a reality, there were also many new opportunities. I should like to thank Gerard Meijer, later succeeded by Aart Kleyn, directors of the institute, for a very constructive and energizing collaboration.

It was also a time in which we stepped up our public affairs efforts, engaging with politicians in the Netherlands and the European Parliament. And here I must mention the great work of Mark Tiele Westra and, my ex-PhD-student and then post-doc, Marc Beurskens – who tragically passed away last month, after a long illness.

When I started at the TU/e as full-time professor, I was also appointed chairman of the FOM executive board. For about seven years that meant an intense and rewarding collaboration with Wim van Saarloos, director of FOM during that time, and for a short time at the end, Christa Hooijer. And with the members of the FOM Executive Board and many of the staff at the FOM bureau.

In 2017 I unexpectedly returned to NWO, as chairman of the Science Domain and member of the Executive Board. Thank you Arian Steenbruggen, director of the Science domain, Stan Gielen and Carolien Visser, chair and vice-chair of NWO, and all colleagues of the Executive and Domain boards. Building up the new organisation was a challenge, but an interesting one.

The members of the complaints committee on scientific integrity that I have chaired for about ten years: if all is well, we have little work, but all is not always well and on those occasions our work has been intense. Thank you, I learned so much from you.

Teaching has always been a great pleasure for me and working with students in graduation projects has been a joy and endless source of new research ideas. Dear students, you inspired me and kept me sharp, and for that I thank you.

In the department, the deans, directors and board members who took up the responsibility to run the department, also in difficult times; and the many colleagues in other groups with whom I had such pleasurable interactions.
In fusion research at TU/e, the many colleagues in multiple departments, and of course at the DIFFER institute, presently led with vision and vigour by Marco de Baar, whom I had the pleasure of guiding during his PhD, 25 years ago.

Tightening the circle further, I come to the fusion group, that we started with a small but very tight-knit team with Clazien Saris – from the very start – Roger Jaspers, Hans Oosterbeek, and Maarten de Bock. Somewhat later expanded with Hélène Kemperman – who retired last month – and Herman de Jong; and with Tony Donné and Guido Huijsmans as part-time professors; and yet somewhat later new energy was injected into the team by Josefine Proll, and Felix Warmer, and parttime members Thomas Morgan and Jonathan Citrin. Working with you all has been a pleasure and privilege, thank you for everything.

I need to say a few more words to Clazien and Hélène: as the group secretaries you have been the stable core of the group and the master's program, keeping us together, looking after staff and students alike, and me in particular, and all with both a smile and unbelievable dedication. And for that I thank you.

And Roger – I can't even begin to mention all the ways in which you have been essential for the group and the MSc program. We have done so many things together: Fusenet, the master's program, educational innovations, …the successes of these are largely yours! All I can say is: a big, big thank you, and keep up the good work! I trust students will flock in in great numbers.

And finally – my personal inner circle. Let me switch to Dutch here.

Mijn ouders, Ben en Ied, zijn al geruime tijd geleden overleden. Maar zij zijn op allerlei manieren aanwezig – en zeker op een dag als deze.
Mijn oudere broer en zus, Ernst, over uit Frankrijk, en Manja – en hun partners Marjolein en Michiel, vaste sterren in mijn firmament zo lang als ik mij kan herinneren.
En de mij door mijn verbintenis met Els in de schoot geworpen geweldige familie Van de Kam: Jan en de onlangs overleden Wil, Anneke en neven en nichten.

En tenslotte, bruisende bron van trots en vreugde, Els, onze kinderen Wolf, Raaf en Rosa – en met Michael inmiddels twee kleinkinderen Abel en Lena.

Ik heb gezegd.

Curriculum Vitae

Prof.dr. Niek Lopes Cardozo was appointed as a full professor of Science and Technology of Nuclear Fusion in the Department of Applied Physics and Science Education at Eindhoven University of Technology on January 1, 1994.

Prof.dr. Niek Lopes Cardozo has spent his entire career in the field of fusion energy, starting with a PhD at Utrecht University in 1985. At TU/e, he initiated the interdisciplinary MSc program Science and Technology of Nuclear Fusion in 2009. Around the same time, he initiated the European Fusion Education Network FuseNet. Before focusing on the training of the new generation of fusion engineers, he worked at the FOM Institute for Plasma Physics (now DIFFER), where he directed the Dutch fusion research program. In that role, he initiated the industrial network ITER-NL, set up to prepare Dutch industry for participation in the large international ITER experiment.

In parallel to his work as a researcher and educator, he has been active in science policy. Among other things, he served on the Executive Board of the Dutch Research Council (NWO), chairing the Science Domain, and before that he chaired the Foundation for Fundamental Research on Matter (FOM), the funding organization for physics research.

Climate change and the energy transition have been longtime interests and concerns. In recent years, his research has focused on the socio- and techno-economics of the energy transition and the potential role of fusion energy therein.

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