Dual Fluid

Reinventing Nuclear

Good for people,
good for nature.

Whitepaper

Introducing fifth generation nuclear by Dual Fluid

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generation nuclear by Dual Fluid

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Executive summary

The welfare of humankind directly depends on the amount of energy available. And nuclear power is one of the most important inventions for generating large quantities of energy. But today's light-water technology converts only a tiny fraction of the energy-rich uranium fuel into electricity. That's why we are developing a more effective method of nuclear fission.

Dual Fluid is capable of dramatically increasing the amount of energy available. Its basis is a **completely new and patented reactor that**

- **potentially reduces the cost for electricity, hydrogen and synthetic fuels to a fraction,**
- **extends the limits to growth and decarbonizes the world economy,**
- **burns nuclear waste, is inherently safe and emission-free.**

The innovation comes from using two fluids in the reactor core. The liquid fuel circulates as slowly as needed for optimal burnup, while the coolant circulates as quickly as needed for optimal heat removal. This results in maximum power density, high operating temperatures and a neutron surplus. Due to its very design, a Dual Fluid reactor can burn any fissionable material, including thorium or natural uranium. A core meltdown or uncontrolled power excursion is impossible.

A small Dual Fluid core with a capacity of 300MW can power 500,000 homes and needs fuel replacements only every 25 years. It generates electricity at about half the cost of fossil-fuel plants. A DF300 core operates about eight to ten times more efficiently than current light water reactors. Power density and efficiency increase further with larger cores. This makes the Dual Fluid reactor the most efficient energy source ever designed.

Efficient energy production goes hand in hand with a very good ecological profile, due to the system's compact size and the small amounts of fuel needed. Total lifetime emissions of a Dual Fluid power plant fall below current nuclear power and even wind power. In fact, Dual Fluid could be used to completely decarbonize our economies within a few decades and to start a new phase of productivity growth.

Unlike nuclear fusion, Dual Fluid is fully achievable with available technology and materials. The DF300 prototype is expected to be operational before the end of the decade.

Cheap and clean energy is the solution to everything **The Dual Fluid principle and its consequences**

The fifth generation

Today´s nuclear technology offers significant potential for improvement: light-water reactors can only convert about one percent of the natural uranium extracted into electricity. The remaining 99% must be disposed of as waste, which increases costs and reduces acceptance.[1] However, because nuclear energy is particularly low-emission and scalable, many players are now trying to improve it. The concepts of the so-called Generation IV focus on safer and more flexible reactors that produce less waste.

But just about all Generation IV designs are versions of concepts conceived in the middle of the last century. Dual Fluid technology, by contrast, is a truly new development. While fulfilling all the goals of Generation IV, our design does reach far beyond this. Our innovation lies in using two liquids in the reactor core: One is carrying the fuel, while the other extracts the heat. This allows the liquid fuel to develop its full power at 1000° C.[2] The high operating temperature, together with the compactness of the system, bring the decisive advantage of unprecedented power density. That´s why we call it Generation V.

High power density means high efficiency, in turn leading to low electricity prices. A small Dual Fluid core with 300MW of electrical power already operates eight to ten times more efficiently than current light water reactors, reducing electricity prices of today´s nuclear or coal-fired power plants by half (see p. 22).[3] With larger cores, efficiency increases further (see p. 11–15).

Also, the high power density further improves the emissions balance of nuclear power, which is already superior to most other technologies. As a result, Dual Fluid is even lower in emissions than wind power (wind and current nuclear: approx. 12 gCO_2eq/kWh[4]; Dual Fluid: approx. 6 gCO_2eq/kWh).

High power density means high efficiency, in turn leading to abundant energy and low electricity prices.

1 The success of light water reactors is based on their military advantages: Reactors with fuel rods are well suited to powering submarines, plus they can provide plutonium for nuclear weapons in an uncomplicated way. Other concepts that were known to be more suitable for civilian use were dropped. The fact that we are still using the same technology three decades after the end of the Cold War is largely due to the immense density of the fuel: it provides so much energy that even poorly performing nuclear power plants are profitable.

2 Today's light water reactors: approx. 320° C

3 A DF300 core, about 60 inches (1.50 meters) high, can power half a million homes.

4 Source: IPCC Report AR5 2014, Annex III

The technology behind it

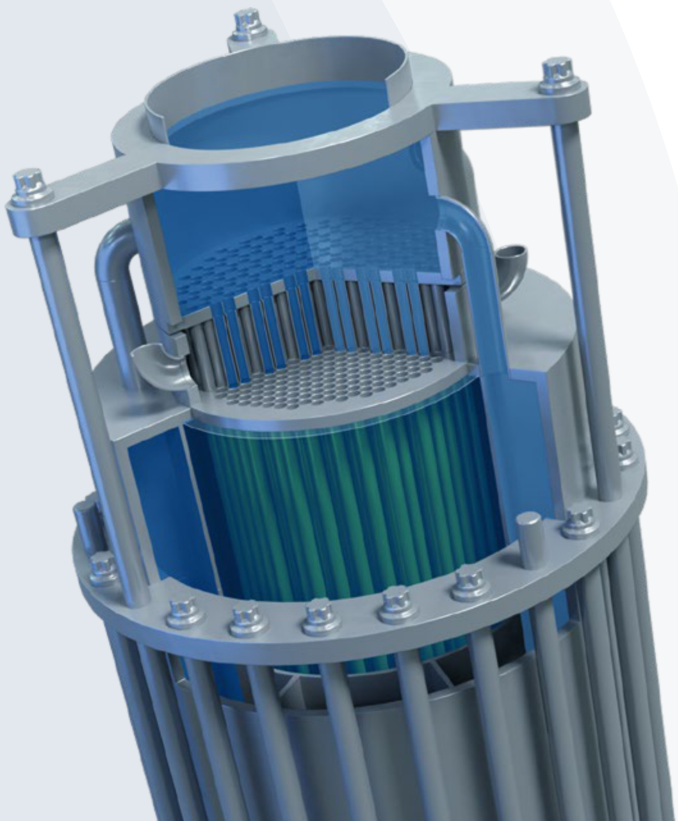
Due to the separate circles for fuel and coolant, the fuel can circulate as slowly as required for an optimum burn-up rate, while the coolant can circulate as fast as required for optimum heat removal. As a result, undiluted liquid fuel – a metallic actinide mixture – can be used, significantly increasing the amount of fissile material in the reactor core. The compactness of the core reduces the amount of structural materials required, so expensive, high-temperature and corrosion-resistant substances can be used. Liquid lead as a coolant dissipates the heat without slowing down the neutrons in the reactor core. This makes the Dual Fluid reactor a fast reactor, characterized by a net neutron surplus, which also serves to deactivate long-lived fission products.

Because Dual Fluid operates with a high neutron excess, the reactor – in combination with the Dual Fluid recycling plant – can fully utilize any fissile material: thorium or natural uranium, plus processed nuclear waste from today´s reactors.[5] The remaining fission products decay rapidly: Altogether, they are less radiotoxic than natural uranium after a few hundred years.

Unlike nuclear fusion, Dual Fluid technology is already achievable with current state of the art engineering. Recent progress in fusion should not obscure the fact that a marketable, namely economic, application is still at least three to four decades away.[6] Even if some companies suggest otherwise, fusion is still at the stage of basic research (especially in the areas of solid-state and plasma physics). In nuclear fission, however, such fundamental questions have been solved for decades.

Synthetic hydrogen-based fuels can power common combustion engines and offer an economically and ecologically attractive alternative to electric propulsion systems.

Separate circles for fuel (green) and coolant (blue) provide optimum burn-up rate with high-capacity heat removal.



5 As the fuel passes through the reactor, its chemical composition changes by transmutation, fission or combustion. The circulation rate of the fuel cycle can be optimized for various purposes, e.g. for maximum burn-up, combustion of transuranics, isotope production, specific deactivation of fission products or others.

6 In the foreseeable future it is impossible for nuclear fusion to compete with coal-fired power plants for one simple reason: Fusion requires lasers or field-generating devices (especially superconducting magnets), which consume a lot of energy and are so complex that they make the systems considerably more cumbersome. This lowers power density, thus efficiency, and increases costs. The fact that a German fusion company recently quoted 5 to 10 €¢ / kWh (5.5 - 11 US¢/kWh) as a realistic price for its electricity confirms this finding.

Clean and abundant energy overcomes the productivity crisis

The use of fossil fuels, which started with coal more than 200 years ago, provided humanity with ten times the amount of energy available before. This soon triggered the industrial revolution. It has been like this since the dawn of mankind: new sources of energy led to leaps in civilization. The innovations of modern times, made possible by powerful energy generation technologies, have freed people worldwide from millenia of living at subsistence level. Productivity and living standards have since improved dramatically on all continents.

However, there has been little progress for several decades now: the productivity of Western countries is reaching its limits because the potential of fossil fuels is now virtually exhausted. The essential innovations that were possible with the available amount of energy have already been realized. On the other hand, many existing ideas are not being implemented today simply because they require too much energy (e.g. applications for environmental protection like carbon capture and storage, CCS, or the production of emission-free synthetic fuels).

If future power plants were to provide ten or twenty times more energy than today's, in relation to the amount of energy required, an enormous surge in productivity and innovation would follow, similar to the first industrial revolution: living standards could improve in ways unimaginable today with the help of completely new technologies. At the same time, nature would regain space – through minimally invasive technologies and new circular economy processes.

Low-cost heat applications decarbonize the world economy

Energy carriers such as hydrogen and synthetic fuels could help to overcome dependence on fossil fuels. But their production is still too energy- and thus cost-intensive.

Today, carbon-free hydrogen can only be generated with high losses of the electrical energy used for electrolysis. Dual Fluid offers an inexpensive source of temperatures of 900 - 1000°C and allows the application of high-temperature steam electrolysis, which is far more efficient than today's processes. Hydrogen can thus be produced at a price that undercuts the present cost of green hydrogen from wind power many times over, in a process that is even cheaper than methane steam reforming (table 3, p. 25).

Synthetic hydrogen-based fuels can power common combustion engines and offer an economically and ecologically attractive, low-emission alternative to electric propulsion systems. The relevant synthesis processes have already been developed, but the price is not yet competitive compared to petroleum products. Concentrated nuclear thermal energy could change this fundamentally: Dual Fluid allows the production of emission-free synthetic fuels at a price that can compete with petroleum-based fuels (table 3, p. 25).

The combination of low-cost, low-emission energy and the high temperatures of a large Dual Fluid power plant offer the opportunity to completely decarbonize the entire energy and mobility sector within a few decades. With large quantities of cheap hydrogen and synthetic fuels, we can simply continue using our existing infrastructure, from vehicles to gas stations.

How nuclear becomes sustainable
Our future power plants

The Dual Fluid principle of separate cycles for fuel and coolant redefines nuclear power: In combination with the Dual Fluid recycling plant, the entire fuel can be used for energy. The residual substances as a whole are harmless after a few hundred years. This eliminates the need for a final repository and makes nuclear more sustainable than any other energy source. Even long-lived radioactive waste that already exists can be fully used as fuel. The amount of waste already produced by nations using nuclear power is sufficient to fully supply them with energy for decades at least (in fact centuries in Germany at today's energy consumption levels).

Even countries that do not have stocks of used fuel can achieve an economically self-sufficient full supply with Dual Fluid. Uranium – and thorium, which has not been usable for nuclear energy up to now –, are found in many regions of the world. Because the energy yield in relation to the amount of fuel is up to a hundred times higher than with today's nuclear designs, the costly extraction of uranium or thorium from very deep layers of the earth would be economically viable. In this way, nuclear fuels would last for tens of thousands of years at least.

The DF300 and DF1500 power plants

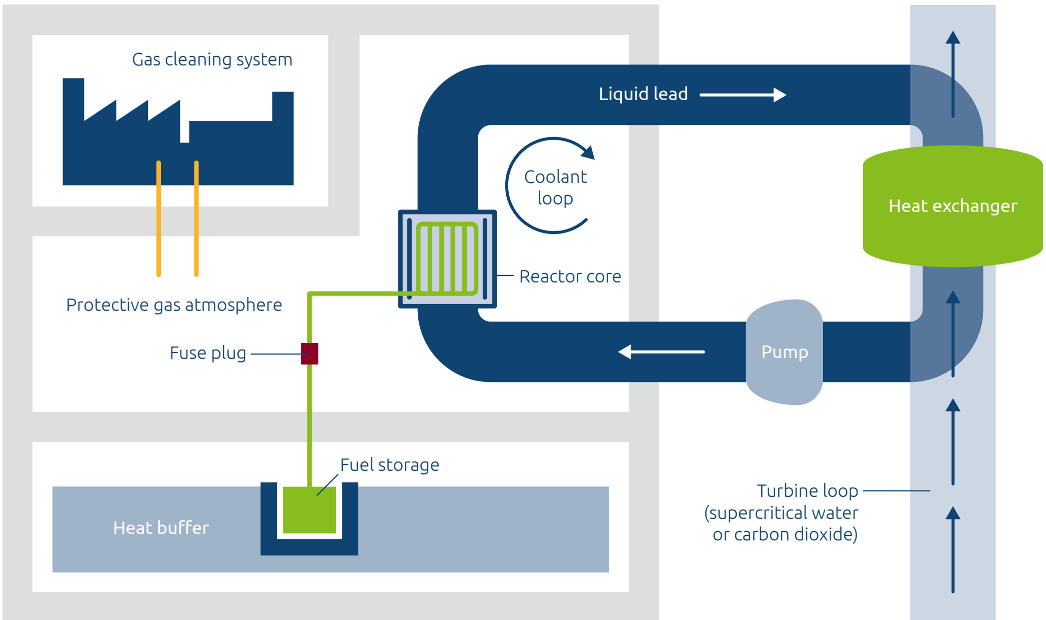
The Dual Fluid principle is independent of the reactor size. The first realization will be a small modular model with about 300 megawatts of electrical power (DF300) which is particularly flexible and affordable. Larger cores with higher outputs (DF1500: 1500 MW_{el} / 3000 MW_{th}[7]) allow highly efficient process heat applications in addition to electricity generation. The electrical energy is continuously and quickly adjustable from zero percent to one hundred percent of the nominal power in both models.

In the DF300 modular power plant **(Fig. 1)**, the fuel is delivered to the power plant in a sealed cartridge. There it is heated and pumped in liquid form into the reactor core, where it produces heat for around **25 years**. A single DF300 core is enough to reliably supply half a million households with low-emission electricity for this timeframe. Several cores together can replace a large power plant. At the end of a combustion cycle, the spent fuel is returned to the cartridge and transported to the Dual Fluid recycling plant (see p. 10) and a new combustion cycle can begin.

Larger cores, such as in the DF1500 power plant **(Fig. 2)**, have a higher fuel throughput and can be combined directly with a recycling unit. This enables permanent fuel processing on site. In addition to electricity generation, the DF1500 power plant (3000 MW_{th}) is particularly suitable for energy-intensive heat applications such as the production of hydrogen and synthetic fuels (see p. 25).

7 MW_{el} = megawatts of electrical power, MW_{th} = megawatts of thermal power

Figure 1: Structure of modular power plant DF300. The fuel is delivered to the power station in a sealed cartridge. It is then heated and pumped into the reactor core where it generates heat for about 25 years. At the end of the burning cycle, the spent fuel is transported to a Dual Fluid recycling facility.



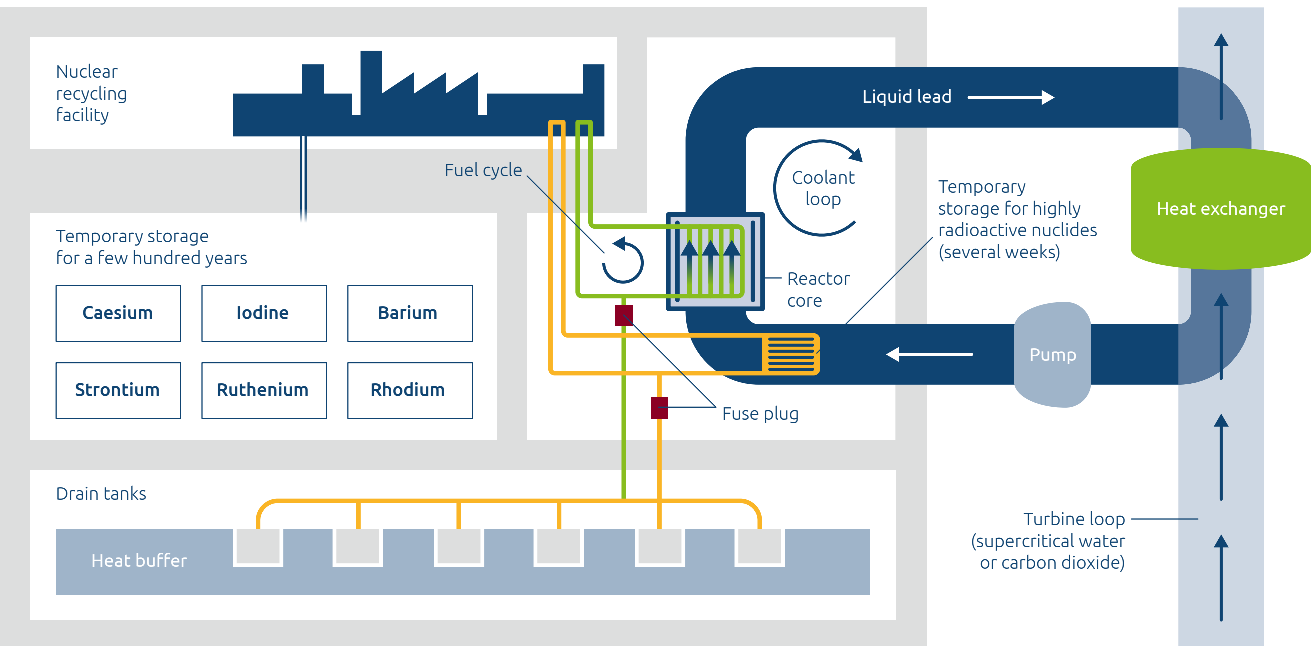


Figure 2: Structure of DF1500 power plant with on-site recycling. The fuel is permanently processed so that all fissionable material is returned to the reactor. Residuals are stored for about 300 years.

The Dual Fluid recycling plant

The Dual Fluid recycling process differs fundamentally from today's fuel reprocessing with PUREX[8] and related wet chemical processes. In the Dual Fluid recycling plant, the spent fuel is first converted into liquid salt form and then cleanly separated into its components using a distillation process that has long been established outside the nuclear industry. All fissionable materials are then mixed with fresh fuel[9] and returned as metals to the reactor core,[10] where they are used to generate energy or converted into short-lived materials. The fission products that can no longer be used are stored in a protected location within the plant until they can be safely disposed of or reused (storage period: approx. 300 years).

This recycling method, based on pyrochemical distillation, enables the complete utilization of any fissionable material. Thus, a true circular economy can be achieved in the nuclear fuel chain for the first time. Since the amount of residual material is as small as the amount of fuel required, the ecological impact of Dual Fluid is lower than with any other form of energy generation. Most of the remaining substances decay rapidly: in total, they are less radiotoxic than natural uranium after a few hundred years.[11]

The pyrochemical recycling by Dual Fluid enables a true circular economy in the nuclear fuel chain for the first time. Long-term repositories for nuclear waste become superfluous.

8 PUREX: Plutonium-Uranium Recovery by Extraction. Historically, the main purpose of this process was to separate the plutonium to build nuclear weapons. PUREX goes along with a side stream of radiotoxic substances.

9 E.g. natural or depleted uranium, thorium, used fuel pellets or long-lived waste from current nuclear reactors. The correct composition of the mixture of materials, which becomes critical in the reactor core, is controlled centrally.

10 For larger power plants on site, for the modular model DF300 as cartridge.

11 Individual substances, e.g. technetium99, emit radiation for a longer period of time. However, if the remaining substances are considered as a whole, the radiotoxicity of the bundle falls below that of natural uranium within a few hundred years.

Why Dual Fluid will outperform competitors **Competitive analysis and energy return**

The energy return on investment (EROI) is a key performance indicator for energy technologies. It describes the ratio of the energy gained to the total amount of energy expended, taking into account the complete life cycle – i.e. construction, operation, fuel, safety, dismantling and disposal of a plant:

$$EROI = \frac{E\ out}{E\ in}$$

A high EROI indicates a favorable ratio of expenditure or demand to yield. An energy return of ten means that a power plant provides ten times more energy during its lifetime than the total amount spent for it to operate, including all ancillary and follow-up costs.[12]

The energy return reveals performance

Fossil-fuel power plants achieve an energy return in the order of magnitude of 30 – in other words, they "earn" around thirty times the total amount of energy used. Solar and wind power, on the other hand, have an energy return of four to nine; including today's energy-intensive storage this figure drops even lower. Obviously, this is not very economical. While an energy return of about 30 powered the industrial revolution and is sufficient to supply an industrial country today, returning to less efficient technologies from the pre-industrial era involves risks: the higher the share of inefficiently produced energy in the overall energy mix, the scarcer and more expensive becomes energy. As a result, the standard of living and the ability to innovate decline. Modern, people- and nature-friendly societies must aim to provide clean and reliable energy in large quantities for little money. A fuel that is denser than coal can achieve that.

Modern, people- and nature-friendly societies need clean and reliable energy in large quantities for little money. A fuel that is denser than coal can achieve that.

12 The energy return reveals energy efficiency on the generation side. While maximum efficiency has long been strived for on the consumer side (in electrical appliances), this idea has been widely ignored on the energy generating side so far.

Today's nuclear power is far behind its potential

Today's light-water reactors have an energy return of around 100, which means that they outperform fossil-fuel power plants by a factor of three in terms of efficiency. That sounds good, but actually indicates serious underperformance because nuclear fission releases not three times, but millions of times more energy than a fossil combustion process. Why does today's nuclear power fall short of its huge potential?

A look at the energy demand in the light water reactor **(Fig. 3)** shows that 80% of it is taken up by provision and disposal of the fuel – i.e. for the mining and refining of the uranium as well as the production, recycling and disposal of the fuel elements. This figure is so high because today's reactors can only convert a negligible proportion of the exploited uranium (1%) into energy. The remainder, mostly mixed with fission products, must be disposed of as nuclear waste. Power generation with today's light-water reactors is therefore a low-yield system.[13] High investment costs and regulatory requirements tend to cancel out the efficiency advantage over fossil-fired power plants.[14] On the whole, the potential of nuclear fission remains mostly unused.

A new generation of reactors („Generation IV") may achieve gradual but not fundamental increases in efficiency. This is because either the concept of fuel rods is maintained, or the concepts build on older liquid-salt reactor designs.[15] In the latter, the same liquid both carries the fuel and provides heat removal, leading to suboptimal results for both purposes.

13 Even low fuel costs do not change this statement. This is because the costs for the entire fuel cycle – including fuel element production and disposal – make the system drastically more expensive.

14 Nevertheless, nuclear power plants still have an efficiency advantage over coal-fired power plants, evident from the cheaper electricity production of amortized nuclear power plants.

15 There are a few exceptions: Moltex Energy's design opts for liquid fuel contained in solid fuel rods. Several players are working on a new version of the pebble bed reactor. Newcleo combines a lead-cooled subcritical reactor with an accelerator. However, none of these approaches is expected to provide great efficiency gains.

Energy demand of a typical light water reactor (LWR)

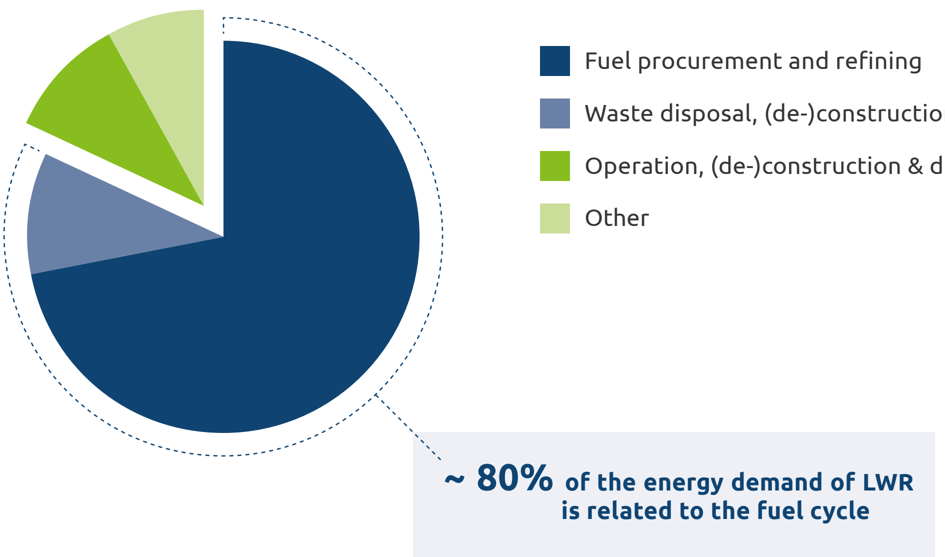


Figure 3: Energy demand of a typical nuclear power plant (light water reactor) with today´s inefficient fuel cycle.
Source: Vattenfall, EPD Forsmark 2009/2010

How Dual Fluid increases efficiency and reduces costs

Our reactor design with concentrated liquid fuel and lead cooling reduces the energy demand for fuel procurement and refining as well as waste disposal to a mere fraction (blue areas, **Fig. 4**). Further efficiency gains result from the relatively compact system with low material demand (green areas, **Fig. 4**).

Energy demand in light water reactors vs. Dual Fluid DF300 (lifecycle analysis)*

	LWR	DF300
Fuel procurement and refining	72 %	1 %
Waste disposal, (de-)construction + dismantling of disposal plants	10 %	1 %
Operation, (de-)construction + dismantling of power plant	10 %	4 %
Other	8 %	4 %
Total	**100 %**	**10 %**

*All values are approximations, based on Vattenfall / own calculations

Figure 4: Energy demand of Dual Fluid (modular power plant DF300): Ten-fold reduction compared to LWR

As the proportion of efficiently produced energy in the overall energy mix grows, energy costs fall, starting a virtuous cycle of abundant energy and economic growth.

Overall, the energy demand for a Dual Fluid power plant – as shown in **Fig. 4** for the DF300 – drops to only about one tenth, and this massively increases productivity. The energy return increases, depending on the reactor size **(Fig. 5)**, to a value between 800 to 1000 (DF300) and 2000 (DF1500).[16] Larger cores would allow further increases up to a value of 5000.

The high efficiency, represented by the EROI (see p. 11), lowers the price of products generated such as electricity or hydrogen. Even the modular reactor DF300 will produce electricity at half the cost of today´s nuclear or coal-fired power plants (see p. 22).

There is a simple reason why electricity is not a tenth of the price, given the tenfold increase in efficiency: the energy used to build and maintain a Dual Fluid power plant is expensive today. Also, items such as labor costs and taxes do not decrease in proportion to increasing efficiency. However, if the proportion of efficiently produced energy in the overall energy mix grows, energy costs fall. Then the high energy return will drive the price of electricity down further, starting a virtuous cycle of low-cost energy and economic growth.

Energy Return on Investment (EROI) = Ratio of the amount of usable energy delivered to the amount of energy required (for construction, fuel, maintenance, safety, dismantling etc. of a power plant)

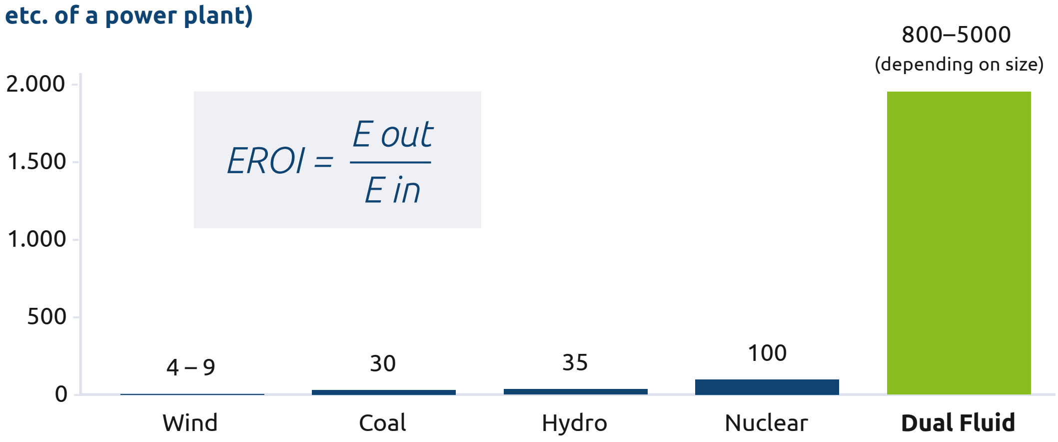


Figure 5: Energy return of current energy sources vs. Dual Fluid

16 Armin Huke et al, *Annals of Nuclear Energy* 80 (2015) 225: „The Dual Fluid Reactor – A novel concept for a fast nuclear reactor of high efficiency“, Daniel Weißbach, Götz Ruprecht et al, *Energy* 52 (2013) 210: „Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants.“

Why Dual Fluid is walk-away-safe
Triple protection

The most important safety feature of Dual Fluid is the **self-regulation** of the reactor. This means that the fission rate automatically follows the energy extraction: If little energy is extracted from the system, the fuel temperature rises. Then the liquid fuel expands. As a consequence, the fission rate automatically drops and so does the fuel temperature. The reactor is therefore completely self-regulating; a power excursion like in Chernobyl is impossible.[17]

In the unlikely event that the system heats up beyond normal operating temperature – conceivable only in case of incorrect fuel composition[18] – the **fuse plug** provides additional safety. The fuse plug is an actively cooled section of the fuel line near the lowest point.

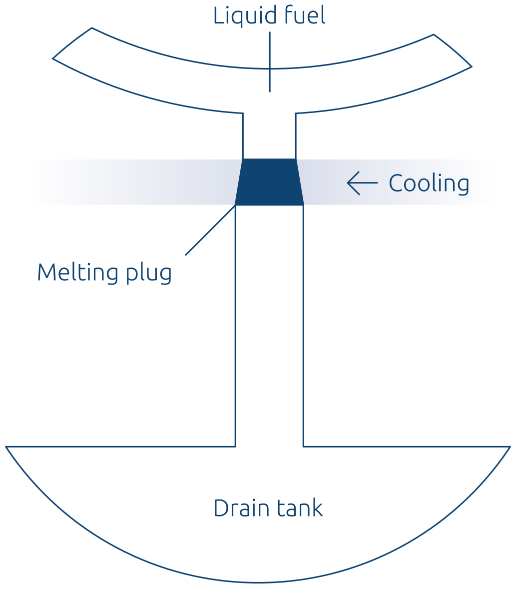


Figure 6: Sketch of the fuse plug. As soon as the cooling fails or is no longer sufficient, the fuel drains downwards into safe tanks and the chain reactions stops immediately.

There the fuel is actively cooled from the outside, so that it freezes out locally and closes the downstream outlet. If the fuel overheats, the frozen fuel plug melts and the liquid drains downward by gravity into subcritical tanks **(Fig. 6)**. The chain reaction stops immediately. In the event of a power failure, the same thing happens because the cooling system fails.

The decay heat is then passively removed from the subcritical tanks, no active cooling is required. This also rules out accidents resulting from residual decay heat not being removed (Harrisburg, Fukushima).

A planned shutdown of the system follows the same principle, so that it doesn´t differ from an emergency shutdown. This simple control system is indestructible and has been proven in the American molten salt reactor experiment of the sixties.

For effective protection against violent impact and earthquakes, the nuclear part of the plant can be located underground in a **thick-walled bunker**. In addition to standard fire protection regulations, an inert gas atmosphere protects against the risk of fire.

Even in the worst possible accident scenario – a leak in the fuel cycle – no radioactive material would escape to the outside, since there is no significant pressure and nothing could explode.

17 Even with today's light water reactors, a power excursion like Chernobyl is basically ruled out. However, they do not regulate themselves automatically by withdrawing power, but require active control technology (including control rods), which makes the reactor more complex and expensive.

18 Causes: Defect or incorrect operation of control unit.

We are creating fifth generation nuclear:
waste-negative, highly efficient and safe.

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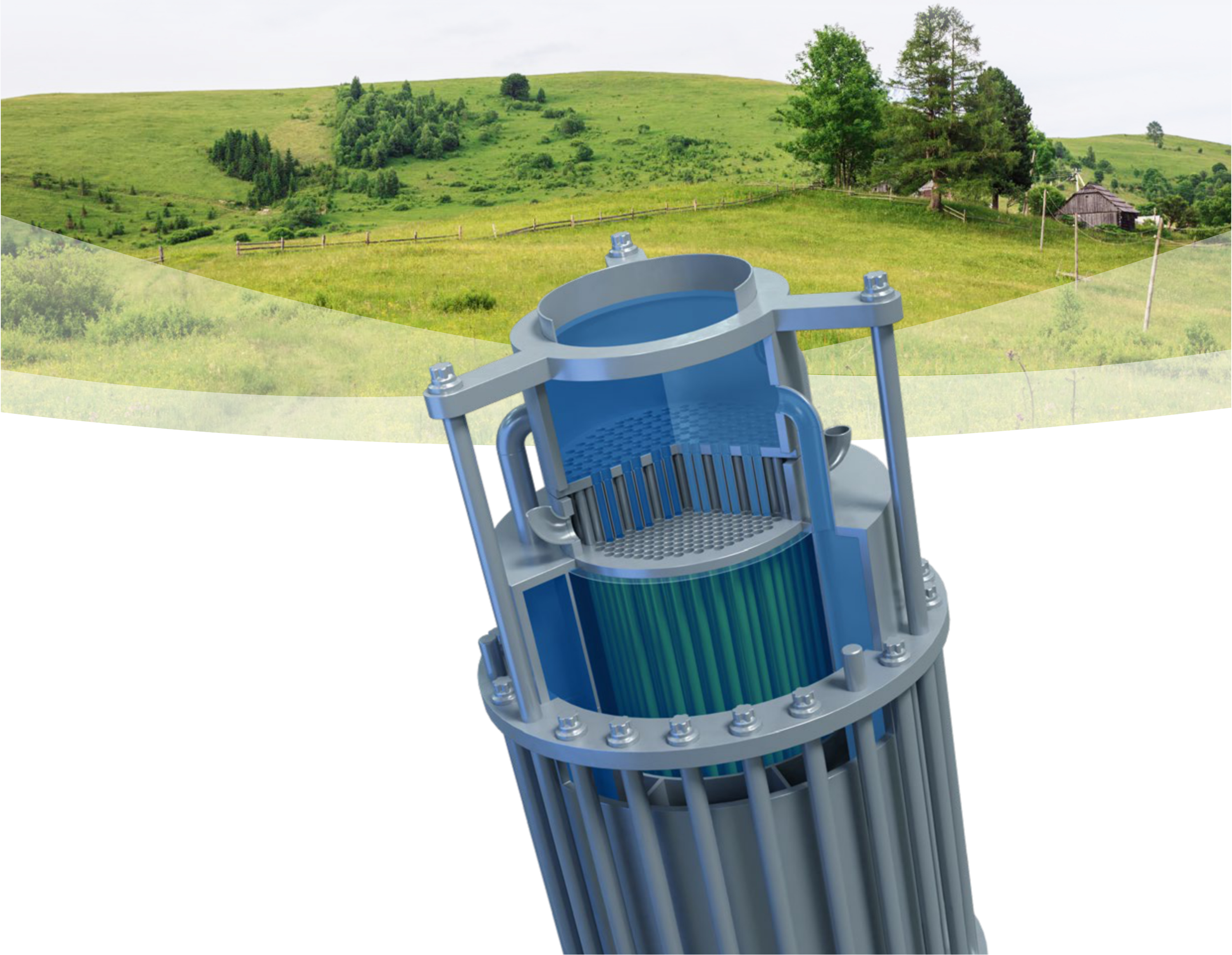

No devil in the detail
Technical questions answered

Material questions

The material separating the two fluids must have sufficient thermal conductivity and corrosion resistance, both for lead and for the fuel which is a molten liquid metal. Compared to conditions in thermal reactors, there is a wide choice of materials for the structural wall mainly because of the low neutron capture cross sections for fast neutrons. Materials that are suitable in principle have in fact existed for decades, but they contain rare and expensive chemical elements. This may be a problem in classical reactor technology and in modern molten salt concepts, since they require large quantities of structural materials due to low power density.[19] But it does not apply to Dual Fluid: as the power density is a multiple, only a fraction of material is required. Therefore, the entire spectrum of modern industrial materials can be used. Even the use of precious metals as components of the alloys will only have a relatively small impact on overall system cost.

Examples of such materials are alloys of refractory metals[20] or highly resistant ceramics such as silicon, titanium or zirconium carbide, which have been increasingly used in industry applications under extreme conditions recently.[21] In addition, heat resistant coatings with substances such as yttrium oxide, which withstands pure uranium up to 1500 °C, can be used. Since the temperatures in the reactor core are significantly lower than this, and the fuel does not consist of pure uranium but of a less aggressive uranium-chromium mixture, it will be a manageable task to identify and develop the most suitable material.[22]

Unlike with thermal reactors, the entire spectrum of high-performance industrial materials can be used.

19 The structural materials for fuel elements, which have to be replaced regularly, are another cost driver of light water reactors. This expense does not apply to Dual Fluid.

20 Refractory metals are corrosion resistant, have a high melting point and expand little when heated. Their heat conductivity is high.

21 There have been great advances in materials technology recently in the field of high-performance ceramics. As a result, a complex product such as a Dual Fluid Reactor core can be manufactured today, unlike two decades ago.

22 The basic suitability of some high-performance ceramics has been proven. Tests must be carried out on the specific construction design of the reactor.

Proliferation and radiation questions

Weapons-grade plutonium can be obtained much cheaper and easier by other technologies than a nuclear reactor. A Dual Fluid power plant would have to be modified completely to extract materials suitable for weapons, because it constantly consumes transmuted fissile material in the core. Regulators would notice such modifications immediately. In fact, the Dual Fluid technology can also utilize plutonium from old nuclear weapons, and thus contribute to nuclear disarmament.[23]

Contrary to frequent popular assumptions, nuclear power plants emit very little radiation to the outside world, so that they pose no danger to humans, animals or nature. Since a Dual Fluid reactor is operated under normal pressure, it will not cause a sudden release of radioactivity as happened in Fukushima. Moreover, because the nuclear part of the plant is bunkered underground, no radioactivity would escape to the outside even in the event of a serious accident or malfunction – not even in the event of the worst accident that can be assumed, a leak in the fuel or cooling circuit. The pressure gradient always directs from the outside to the inside.

23 A few weeks after weapons-grade plutonium is fed into the reactor, it becomes useless for weapons. Plutonium from today's reactors is already not viable for weapons.

Isn‘t this for governments only?
Well, the world has changed

In the past, large-scale projects such as space travel and the development of new energy sources were seen as a state responsibility, because only governments could raise the huge sums required. The disadvantage is that governments pursue political interests and have little incentive to work economically and efficiently. Free competition, in which the most suitable and profitable concepts can prevail, tends to be blocked by a state-funded energy sector, for example. The energy crisis we are facing today is primarily the result of government misdirection of investments.

Today, however, the networked and globalised economy has the capacity to finance competitive developments even in particularly capital-intensive sectors. Various well-known entrepreneurs compete in space projects and have developed highly cost-effective solutions. Given the enormous amounts of money already invested in those projects, private investors should also be able to invest billions of dollars to develop a Generation V nuclear reactor. As is the case in the space industry, this will be done in close consultation with national and international authorities. But it is no longer true that only governments can finance such large-scale projects using taxpayers‘ money.

Dual Fluid will significantly reduce the cost of nuclear power for several reasons:

» the entire system is significantly more compact than current light water or molten salt reactors and thus enables serial production,

» it operates under normal pressure and there is no need for positive pressure containment,

» as decay heat is passively removed, there is no need for an emergency cooling system,

» it reduces the amount of fuel needed to a fraction.

Costs for prototype and serial production

All information and cost estimates in the following sections are based on solid and publicly available sources as far as they concern existing technologies. The figures on Dual Fluid were thoroughly elaborated by the authors. All sources and calculations are available on request.

The development costs for the prototype of a DF300 reactor amount to approximately 6 billion US$ (time horizon: approx. 8 years). Including the manufacturing facility for serial production, a grand total in double-digit billions will be required (total time horizon: 13 to 14 years). A higher capital outlay would accelerate the prototype development to approximately 6 years and series production to 8 years. Development of the DF1500 model with its fuel recycling system (the pyrochemical processing unit, PPU) will require investments again in the low double-digit billion range. It is planned to finance this development from the revenues generated from the first DF300 sales.

Investment costs for utility operators

As soon as serial production starts, utilities may purchase a Dual Fluid power plant. The total investment costs of the operator for a DF300 will amount to approximately 1.1 billion US$. Herein included are the purchase price of the entire DF300 system, land purchase, construction planning, permissions, construction of surrounding buildings, construction interest, management cost, and a contingency. This leads to specific investment costs of approximately 3.5 US$/W in electric power. Time-to-market for the DF1500 power plant is planned for some 4-5 years after production start of the DF300. Total investment costs for operators of the DF1500 have been estimated to amount to approximately 4 billion US$, or specific costs of 2.7 US$/W in electric power.

Electricity costs

Levelized Cost of Energy (LCOE) comparison

Electricity costs are usually compared using the Levelized Cost of Energy (LCOE): To calculate the LCOE, all amounts invested for building, fuelling, operating and decommissioning a power plant over its entire technical lifetime are summed up and divided by the total output of electrical energy, again over the entire technical lifetime of the power plant. **Table 1** shows an LCOE comparison of Dual Fluid with today´s nuclear power, coal and gas.[24]

Levelized cost of energy (LCOE)

	DF300	DF1500	Nuclear today	Coal	Gas CC	Gas OC
LCOE US$/MWh	27	21	65	55	70	95
LCOE US¢/kWh	2.7	2.1	6.5	5.5	7.0	9.5

Table 1: LCOE comparison between different energy generation types (sources except Dual Fluid: World Bank, 2020). Gas CC = combined cycle, Gas OC = open cycle turbine; Gas OC is easier to regulate and therefore preferred as backup for volatile solar and wind energy.

LCOE values for wind and solar power are comparable to coal or lower, depending on location and system used. However, an LCOE comparison would be misleading, because solar and wind power require high additional costs for storage and grid expansion. Most importantly, they cannot supply the base load that is essential for any power grid.

The LCOE values of Dual Fluid are significantly below the values of other thermal power plant types: Compared to coal and nuclear today, **DF300 will halve the electricity costs. DF1500 reduces costs further.** The taxation of carbon dioxide emissions further increases the price advantage of Dual Fluid.

24 In accordance with industry practice, the annual values of cost (in the nominator) and energy production (denominator) were discounted by a fixed rate of seven percent.

Full cost comparison of electricity produced

In contrast to the LCOE, which indicates the average electricity price over the entire lifetime of a power plant, a full cost analysis details out the cost structure for operating the plant. The first year of operation is the most expensive year. Thereafter, interest and depreciation costs decrease from year to year. **Table 2** shows a full-cost comparison between Dual Fluid and other power generation types, with the values of Dual Fluid referring to the most expensive first year of operation. Values for existing nuclear, coal and gas power plants are average values over the technical lifetime of the respective power plant types. A full cost figure below 50 US$/MWh makes the **DF300 substantially cheaper than any other power station even in the first year of operation.** The main reason, apart from relatively low capital costs, is the low fuel consumption. With the DF1500, there will be a further cost reduction potential in the power markets. With first year's marginal costs of 9.2 US$/MWh and full costs of 29 US$/MWh, the DF1500 will position nuclear energy at half the cost of other thermal power plants.

Full cost comparison of electricity produced, US$/MWh

	DF300	DF1500	Nuclear today	Coal	Gas CC	Gas OC
Operational cost	5.1	2.0	4.6	5.4	3.3	5.6
Fuel cost	0.5	0.2	8.8	27.9	44.3	60.0
Maintenance cost	9.8	7.0	11.9	5.0	2.8	3.4
Marginal cost	**15.5**	**9.2**	**25.3**	**38.3**	**50.3**	**69.0**
Capital cost, taxes, depreciation	32.6	19.9	51.4	28.3	16.7	19.6
Full cost	**48.1**	**29.1**	**76.7**	**66.7**	**67.0**	**88.6**

Table 2: In a full-cost comparison, Dual Fluid undercuts all other technologies significantly. Values of Dual Fluid are calculated for the most expensive first year of operation. All other values are average values over the lifetime of the power plant (source: World Bank, 2020). Gas CC = combined cycle, Gas OC = open cycle turbine; Gas OC is easier to regulate and therefore preferred as backup for volatile solar and wind energy.

Hydrogen and synthetic fuel production costs

Hydrogen

Current steam reforming from methane and similar processes are CO_2 -intensive and consume fossil fuels. With the high temperature of a Dual Fluid reactor, emission-free hydrogen can be produced from water by catalytic thermolysis at high efficiency.

Already the DF300 can produce hydrogen at a price that competes with current steam reforming: **1.2 – 1.5 US¢/MJ.** The DF1500 will lower the price to **0.9 – 1 US¢/MJ**. For comparison: Emission-free hydrogen from wind power costs 6 – 8 US¢/MJ.

Hydrazine

Hydrazine hydrate is a liquid fuel with properties similar to benzine (including toxicity). Produced by nuclear energy, it becomes an affordable alternative to petroleum products for use in transport. It can be combusted in piston engines of vehicles and in turbines of aircraft after minor modifications.

The large DF1500 can provide hydrazine at a price competitive with today's oil-based fuels: **0.6 – 1.1 US¢/MJ** (depending on the process used).

On a per-energy basis, the hydrazine-producing Dual Fluid facility can compete with oil production costs equal to or higher than 40 US$ per barrel. On a per-weight as well as on a per-distance basis, only oil fields suitable for primary oil recovery (e.g. Middle East) can compete. These resources are expected to be depleted first and in the foreseeable future.

Overview: Fuel production costs, conventional and using Dual Fluid

Method	Total US¢/MJ[25]			
	conventional	**DF300**	**DF1500**	**DF30G**
Refined oil (Middle East)	0.27 – 0.31	0.30–0.34	0.25 – 0.29	0.24 – 0.27
Refined oil (oil sands, Canada) [26]	**0.75 – 1**	0.8 – 1.1	**0.6–0.9**	**0.5 – 0.7**
Hydrazine production	2.4	1.3 – 1.7	**0.8 – 1.1**	0.5 – 0.8
Hydrazine production, direct splitting (e.g. SSAS)	2.0	1.0 – 1.4	**0.6–0.95**	**0.4–0.6**
Hydrogen production, S-I cycle or Hot ELLY	1.8 – 2	**1.2 – 1.5**	**0.9 – 1**	**0.7 – 0.8**
Hydrogen (methane/steam reforming, 2 US¢/kWh)	**1.3 – 1.5**	-	-	-
Hydrogen from wind energy	**6 – 8**	-	-	-
Ammonia production	1.3	0.7	0.45	0.35
Ammonia production, direct splitting (e.g. SSAS)	0.8	0.4	0.25	0.18

Table 3: Fuel production costs conventional / Dual Fluid. The bolded values facilitate the most important price comparisons.

Business case and product pipeline

Dual Fluid will generate revenues mainly from the sale of reactors once serial production has started. The first DF300 reactor has a thermal output of approximately 600 MW and an electrical output of approximately 300 MW.

DF300 will be offered at a price of around US$ 3,000 per kilowatt. This will allow buyers to earn a net return of approximately 9 % IRR at a 40 US$/MWh power sales price. The purchase price includes fuel supply for approximately 25 years. After this period, Dual Fluid takes care of the removal of the used fuel and the delivery of new fuel.

The Dual Fluid reactors are to be identical to each other and will have undergone type approval in order to minimize the approval process for the customer. Serial production is to be set at 50 units per production line per year. In today's currency, the sale of all reactors produced would generate potential revenues of US$ 45 billion per year.

25 Heating values of oil-based fuels, hydrazine, hydrogen and ammonia are ~42 MJ/kg, 19 MJ/kg, 125 MJ/kg and 18 MJ/kg, respectivly

26 Canadian Oil Sands Supply Costs and Development Projects (2016-2036), 2017, Canadian Energy Research Institute (CERI)

The annual cost of manufacturing will be approx. US$ 10 billion. Accumulated development costs (approx. US$ 20 billion) must be financed from the surpluses. For the time being, remaining profits will not be distributed to investors, or only to a small extent, but will be used to develop further product lines. These are, in particular, the recycling plant (PPU / Pyrochemical Processing Unit), the large variant of the power plant with approx. 3,000 MW thermal and 1,500 MW electrical capacity (DF1500), as well as the variant for fuel production DF30G with approx. 30,000 MW thermal capacity, in which carbon and nitrogen-based fuels as well as basic chemicals for the chemical industry are to be synthesized. The target cost of energy for the larger variants is about 10 US$/$MWh_{el}$ for DF1500 and 3 - 4 US$/$MWh_{th}$ for DF30G.

In further development steps, new applications for nuclear technology are to be developed, such as nuclear batteries offering a service life of several decades, which could be used in all kinds of mobile applications or in small stationary plants.

This development plan results in an assumed valuation of Dual Fluid in the range of US$ 150 billion at the time serial production starts. If the considerable growth potential is priced in, this value could be exceeded many times over.

To ensure that several dozen DF300-class reactors can be sold from the first year of series production, the level of awareness of this technology must increase. This should succeed in particular because Dual Fluid technology is disruptive: it produces energy at significantly lower cost than fossil fuels while being CO_2 emission-free and environmentally friendly. This message will go a long way towards gaining the necessary support from decision-makers in politics, business and the media. The planned IPO in the middle of the decade will help to raise the profile.

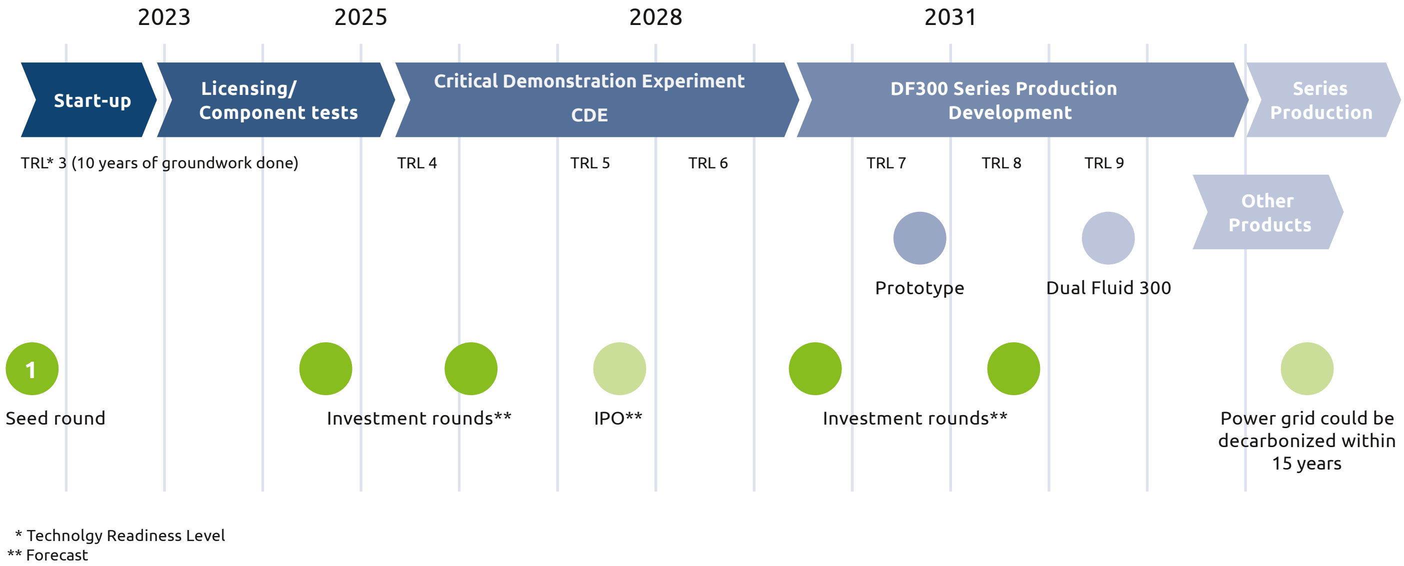

Figure 7: DF300 - Serial production readiness within a decade. The seed round was successfully completed in June 2021.

Publications

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Chunyu Liu et al, *Metals* 10 (2020) 1065: "Thermal Hydraulics Analysis of the Distribution Zone in Small Modular Dual Fluid Reactor"

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Xiang Wang, Dissertation, Technical University of Munich, Chair of Mechanical Engineering (2017): "Analysis and Evaluation of the Dual Fluid Reactor Concept"

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Dual Fluid

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