Dual Fluid Reactor - IFK

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The **Dual Fluid Reactor**, DFR, is a novel nuclear reactor concept based on the Generation IV Molten-Salt Reactor (MSR) concept and the liquid-metal cooled reactors (SFR, LFR) with the major improvement that the molten-salt fuel is not used as coolant but the heat is removed in a separate liquid-lead loop.

The DFR was invented by members of the Institute for Solid State Nuclear Physics (Institut für Festkörper-Kernphysik, IFK) and an associate member. A patent is pending and the IFK is currently seeking public and private funding.

Properties of the DFR

Most advantages result from the fast neutron spectrum and the integrated online fuel cycle. Specifically, these are:

- Naturally existing fissile materials are completely consumed by the DFR. Assuming a full global energy supply that provides Western living standards, natural uranium resources can last several million years. For all this time, the extraction of fissile material can be sufficiently provided by almost every nation for itself, therefore eliminating energy dependencies to a great extent.

- The DFR uses all fissionable actinides almost completely, including the transuranium elements from today's interim storage facilities. Moreover, it transmutes fission products, so that the remnants have to be stored only for 300 years.

- Due to the high power density and the fact that additional reprocessing and enrichment plants are not required, a commercial DFR can be operated compactly at a fraction of the cost of a common modern pressurized water reactor.

- The DFR is inherently safe, thus does not need any active safety systems as opposed to present water moderated reactors. It cannot become supercritical in any operational status or fault.

- As a system that is mainly operated automatically and self-contained, the DFR can be monitored and encapsulated against unauthorized access from the outside. Transmuted fissile material will be consumed continuously in the core, hampering any attempt of proliferation.

- Due to the high operating temperature the DFR can be constructed without water cooling, thus allowing a relatively unrestricted choice of the location. In particular it can be operated subterraneously, therefore strongly reducing the danger of natural disasters, other accidents (airliner crashes), or intentional attacks.

- The high operating temperature of the DFR allows for cost-effective process chemistry, for instance a major industrial production of fuel (also with CO_2-free combustion) considerably less expensively than with petroleum-based fuels.

- Water can be desalinated on a large scale without affecting the simultaneous electricity production of the DFR plants.

How the DFR works

Historical concepts

Nuclear Energy today

The discovery of nuclear fission was probably the most important event in science history. It offers a sustainable and extremely safe energy supply sufficient for all humans. Nuclear fuel resources are available in all countries in amounts that are sufficient for millions of years.

This is in stark contrast to the way nuclear fission energy is "produced" these days. Barely one percent of the original natural uranium mass is used up in the fuel rods for energy production in water-cooled reactors, the remainder is treated as radiotoxic waste, transported around the world, perhaps recycled, and eventually buried deep-underground (somewhere at some point in the future). Moreover, the nuclear fuel is burned at an inefficiently low temperature, which is too low for any interesting chemical applications.

However, despite its inefficient use, the energy density of nuclear fuel is so vast compared with other energy carriers (or compared with solar irradiation density on Earth) that the advantages of those reactor types still prevail, even after 60 years of basically unchanged technology, though safety has been improved as much as possible. However, the established fuel enrichment/recycling industry working hand in hand with the nuclear waste transportation and the nuclear reactor industries has resulted in stagnation of the entire field. These structures are so settled and well entrenched that there is no interest in other nuclear reactor systems. There is a closed enrichment/recycling/waste market that does not permit waste-free or enrichment-free nuclear concepts were proven to be reliable and more efficient half a century ago.

The Generation IV concepts, though feasible today, are postponed to the future by decades. In particular the MSR was tested in the late 1960s in the U.S., running for years with great success. The thorium high-temperature reactor THTR was developed in Germany in the 1970s, also running for years with great success. All these market-ready developments could not penetrate the well-established fuel enrichment/recycling/waste industry based on the ineffective pressurized water reactor technology.

The water-cooled fuel rod technology emerged essentially from the first military concepts of mobile nuclear reactors for the specific propulsion of naval submarines and carriers. This technology, together with the fuel enrichment and recycling industry, is not really made for civil applications, however, it is established all over the world and is now the only available reactor technology on the market. It is expensive, produces a lot of nuclear waste, and needs a complex infrastructure.

The MSR concept

The MSR experiment (MSRE), performed in the 1960s at Oak Ridge National Laboratory, proved that the molten-salt technology is reliable and easy to handle. All material problems were solved and the test reactor was running for years. However, it was still a thermal or epithermal type of reactor which typically produces more actinides than it burns. Recently, a calculation performed by members of the Generation IV forum has shown that the MSR works even better with no graphite moderator at all, making it a fast neutron type of reactor.

The efficiency of the MSR is reduced by the double function of the fuel to also act as coolant. As a result, the molten salt used had to be diluted in order to limit the power density, otherwise the heat could not be removed fast enough. Furthermore, salts with low melting point are necessary for the effective utilization of a heat engine. In addition, the salt has to circulate fast for efficient cooling and that, in turn, prevents any on-line reprocessing of the fuel. The fuel, thus, needs to be processed off-line (but still on-site) at regular intervals. Off-line processing of the fuel requires long shut-downs, further reducing the efficiency of the overall system. Several techniques exist that improve the fuel cycle by extending the intervals between shut-downs, however, these techniques worsen the neutron economy and thus reduce the transmutation turnover.

Lower power density means a larger reactor volume which allows the use of cheaper and well workable structural materials. However, these materials suffer from corrosion problems at high temperatures, aggravated by the unavoidable production of significant amounts of hydrofluoric acid during the regular operation of the reactor. This problem limits the operation temperature of the reactor core to 650 °C.

Liquid metal cooled reactors

Liquid metal as coolant simultaneously renders the neutron spectrum fast and allows for the heat removal of a high powered core which is implied by the low cross sections of fast neutrons. Contrary to water coolant a costly pressure vessel is not required. Historically, the envisioned application of a high powered metal cooled reactor for the propulsion of strategic bombers in the 1950s caused a lasting fixation on sodium as coolant in spite of its engraving disadvantages because of its low density which was mandatory for the airborne reactor project. Consequently, all experimental fast reactors up today were cooled with liquid sodium. A fast reactor that was actually deployed powered the soviet Alfa class submarines and used a liquid lead bismut alloy as coolant. The Alfa submarines were in operation for 2 decades and were decommissioned at the collapse of the USSR. Both reactor types joined in the generation IV canon.

Nowadays concepts for larger power plants place the reactor core inside a multiple times larger pool of the liquid metal coolant in order to remove by convection the residual heat from the decay of fission products accumulated in the fuel rods in case of a loss-of-power accident . Sodium, besides its well known aggressive reaction with air and water also has disadvantageous neutronic properties. In comparison to lead it has a considerably higher neutron absorption cross section with resulting activation and still sizable moderation quality. A softer neutron spectrum also reduces the neutron economy since the number of released neutrons per fissioned nucleus inclines with the incident neutron's energy. The high neutron absorption of sodium in combination with its low boiling point (883 °C) may enable a temporary positive void coefficient with a power excursion when sodium vapour bubbles form and reduce the neutron absorption (a density decrease in lead reduces foremost the neutron reflection). As a countermeasure a pressure vessel for the reactor pool and an intermediate sodium coolant loop is necessary because of the high radiation intensity of activated sodium and its flammability in case of a leakage in the steam generator is necessary. In summary, all of these measures render SFR's uneconomical in comparison to water cooled reactors.

Absorption of neutrons by nuclei in the liquid-lead coolant produces most frequently stable nuclei again. So even after long operation the radioactivity of the coolant is low. Together with the chemical inertia of lead, an intermediate coolant loop is obsolete. The excellent neutronic properties of lead offer many options for reactor design, including long refueling cycles, since neutron poison from fission products is less impairing, and maximized transmutation performance. The high boiling point of lead (1749 °C) enables operating temperatures in the very high temperature range, suitable for process chemistry. However, the LFR concepts remain stuck at temperatures below 700 °C because the employed exchangeable fuel elements require cheap structural materials which are dissolved by liquid lead at elevated temperatures. The dissolving properties of liquid lead towards steel are to be reduced by aluminium plating and regulated oxygen admixture to the lead.

The DFR concept

The DFR incorporates elements of the MSR and liquid-metal cooled fast reactors and extends their advantageous properties.

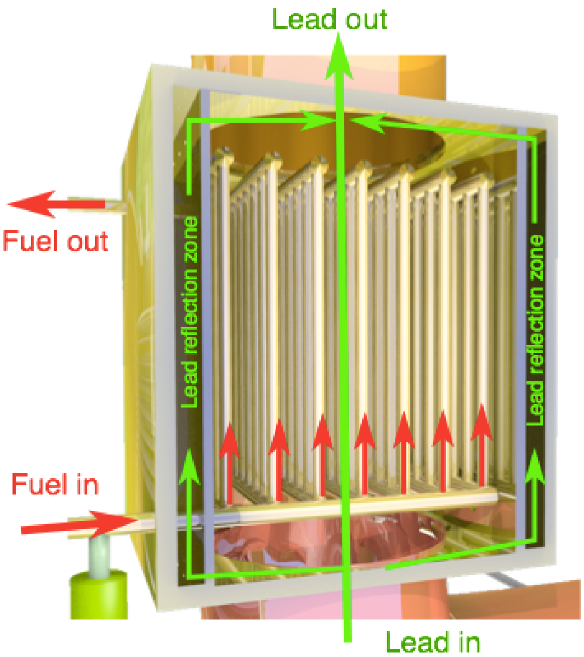

Figure 1. Dual Fluid reactor core. The number of tubes, actually ten thousands, is reduced for illustration.

The key feature of the DFR is the removal of the heat by a separate coolant loop, contrary to the MSR where the heat has to be removed by the fuel itself.

Using separate loops for fuel and cooling has many advantages while it simplifies the overall concept. It allows for a very high power density going along with inherent safety thus rendering the DFR very economically competitive. A main advantage is that the DFR works with very fast neutrons and a very high neutron excess. The high neutron excess can be used to dispose of long-lived nuclear waste produced by todays thermal reactors, in parallel to its own power production. The DFR can be built at low costs without the need for extensive material research.

The fuel can now circulate as slowly as necessary to provide an optimum burn-up rate while the coolant can circulate as fast as necessary to provide the best heat removal. As a consequence, undiluted molten-salt fuel can be used and the amount of fissile materials in the fuel can be increased significantly. This not only boosts the power density but also raises the fuel's boiling point and therefore allows for a very high operational temperature. This combines the advantages of the Generation IV concepts of the MSR and the VHTR.

As the choice of coolant materials is not restricted by the fuel anymore, liquid lead can be used which not only has the advantage of an excellent heat transfer but also makes it possible to operate the DFR as a fast reactor. Fast reactors have a net neutron excess which can be used for breeding or for the deactivation of long-lived fission products. This is further amplified by the employment of chlorine salts (preferable ^{37}Cl) which are much less neutron moderating and corrosive than fluorine salts.

The material which separates the two fluids must have sufficient heat conduction and resistance to corrosion by the salt and the liquid metal. In comparison to the conditions in thermal neutron reactors the choice of nuclides for the structural wall material opens widely because of the low neutron capture cross sections for fast neutrons. Appropriate materials were developed decades ago; however they contain rarer and more expensive chemical elements. Contrary to solid fuel elements which are changed regularly, all DFR materials remain in the core and so even rare noble metals might be used as ingredients for the alloys with low impact on the total costs of the plant. Examples for such materials are the alloys of the refractory metals which are being used more and more in heavy duty applications in industry over the past decades.

In this manner the DFR solves the material problems of the MSR as well as the LFR which both must rely on cheaper materials in order to remain economically feasible.

Physical control loops

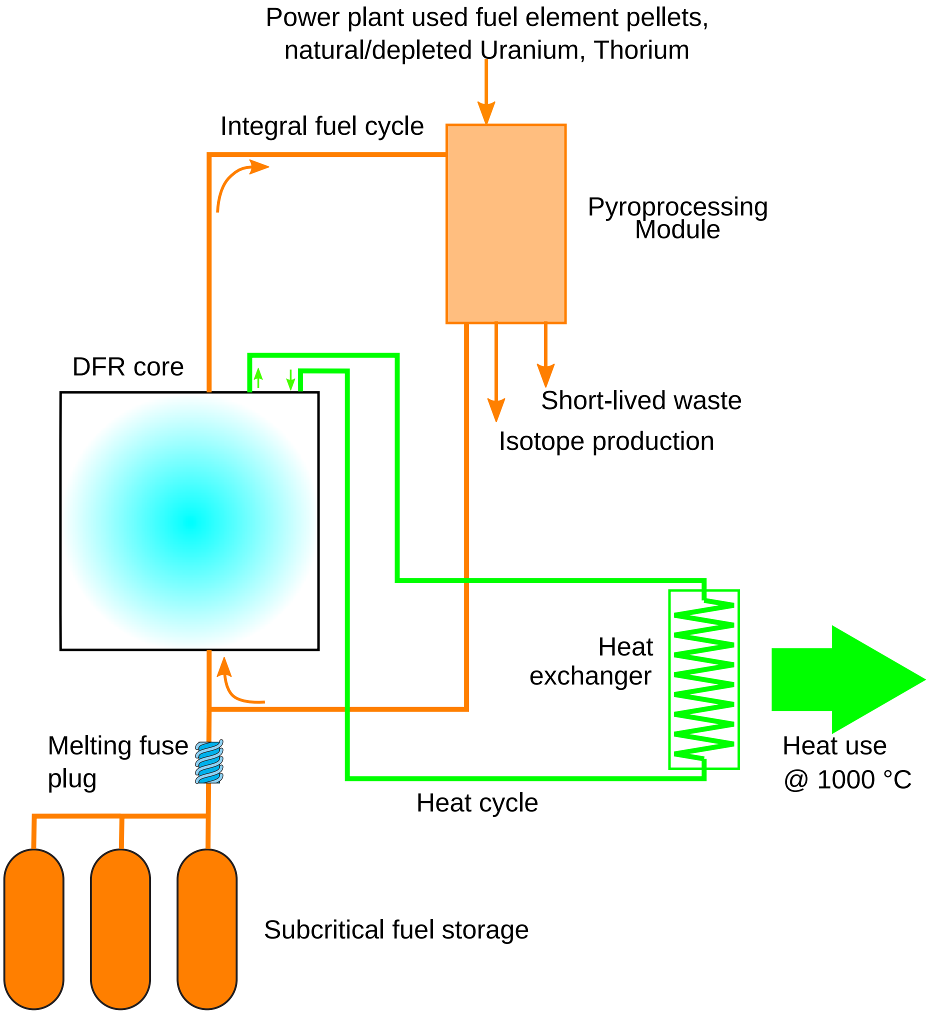

Figure 2. Dual Fluid reactor physical control loops

The two loops, for the fuel (red) and for the coolant (green), are shown in the figure. The liquid lead coolant leaves the reactor core at a high temperature and moves into the heat exchanger where it transfers heat to another medium. It leaves the heat exchanger at a lower temperature and enters the reactor again.

When the molten-salt fuel moves through the reactor the chemical composition changes by transmutation, fission or breeding. The chemically modified fuel leaves the reactor core and enters the pyroprocessing unit (PPU). Here, short-lived fission products, medical isotopes, or bred actinides are separated out while natural or depleted uranium or thorium, used fuel pellets or long-lived waste from conventional nuclear reactors can be mixed in. The PPU provides the right mixture that becomes critical in the reactor core.

The circulation speed of the fuel loop can be adjusted for various purposes such as maximum burn-up, transuranium element incineration, isotope production, fertile material conversion (aka breeding), specific deactivation of fission products, etc.

A very important property of a nuclear reactor is the temperature coefficient. If positive, the fission rate increases with temperature which can lead to dangerous power excursions as it happened with the Chernobyl reactor. The temperature coefficient of the DFR is negative, so deeply that the reactor is self-regulating: The fission rate follows the power extraction. If the lead circulation slows down, the fission rate slows down as well.

The melting fuse plug (already proven for the MSR) is a fuel duct section that is constantly being cooled so that the molten-salt freezes in it and seals it up. The DFR is shut down by simply stopping the power supply for the fuse plug which melts it, allowing the molten-salt fuel to flow into the subcritical storage tanks where the low residual decay heat can be removed passively. The same happens in case of a power outage or in case of a core temperature that is too high. There is no difference between a regular and an emergency shutdown. Therefore, for all known typical dangerous reactor accidents like 'loss of power accident', 'loss of coolant accident', 'criticality accident', 'decay heat' the DFR behaves well mannered like for a regular shut down.

Those safety features originating from the MSR are combined with the excellent neutronic properties and the high heat transport capacity of liquid lead coolant into a compact reactor core with a very high power density and all the same inherent safety. Thus the technical prerequisites are in place to render the DFR the most cost-effective power generation system.

Transmutation

In contrast to present reactors the transmutational power of the DFR can be maximized because of its optimal neutron economy. This is achieved by the design and the continuous removal of fission products (neutron poisons).

0.2 neutrons per fission are already sufficient for the continuous processing of the self-generated long-lived burn-up; thermal reactors do not have the necessary neutron excess. In the DFR fissioning plutonium 0.6 neutrons or more are available for that, thus at least 0.4 neutrons may be used for the transmutation of external fission products.

Inside a 1 GW_{th}-plant up to several kilograms of additional fission products would be transmuted annually, leading to a reduction in amount of long-lived isotopes in the interim storage facilities. In the pyrochemical facility valuable materials for other applications can be extracted from the stable fission products. In addition, up to 400 kg of transuranium elements may be fissioned.

According to the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz) 100 tons of transuranium 'waste' will have been produced by the existing nuclear power plants until the year 2040. Through transmutation of the transuranium elements the storage time for the radioactive waste is reduced from several 100,000 to some 100 years. Simultaneous transmutation of long-lived fission products limits the necessary storage time to 300 years.

If the neutron excess is employed for the transmutation of fertile material (^{238}U, ^{232}Th) the DFR operates in the breeder mode. With the U-Pu cycle the DFR has a doubling time for the initial inventory of another reactor down to 4 years. Hence the doubling time is comparable to the total construction time of a power plant and not the limiting factor for deployment. For comparison, SFR's (like the french Superphénix and the russian BN) together with PUREX-reprocessing plants have doubling times of 30-40 years. Utilizing the Th-U cycle in water cooled reactors with fuel elements would exceed even these long doubling times. The thermal thorium MSR (aka liquid fluoride thorium reactor - LFTR or "lifter") has a doubling time of 25 years. This is because the fission of ^{233}U yields considerable fewer neutrons. Though in the very hard neutron spectrum of the DFR even the neutron yield of ^{233}U would improve.

Heat Utilization

The heat Utilization module for electricity production consists of a closed supercritical water cycle with turbine generator pairs. The electric efficiency of the system would be about 50%. The residual heat content after the turbine needs to be discharged. This can be accomplished in the usual way as for any other power plant such as sea water cooling at coastal locations, wet cooling tower, and dry tower cooling. The last option is most wearing on the efficiency but does not rely on a constant water supply while for the first option it is parenthetically possible to cheaply desalinate sea water since the coolant temperature is still high enough.

DFR systems can be equipped with specially manufactured heat exchange modules for the transduction of chemical process heat for different industrial purposes. Here, peripheral technology being developed for the VHTR can be employed. In combination with electricity producing DFR's any industrial plant can be energized completely nuclear.

The technical properties of the DFR like high operating temperature and liquid metal coolant enable further development options for the conventional part. One option is a noble gas turbine instead of supercritical water. Another option is the installation of a magneto-hydrodynamic generator in a liquid metal topping cycle reducing the size of the turbo-generators and the overall costs while increasing the efficiency. A similar possibility is an AMTEC (Alkali-metal thermal to electric converter) which has no moving parts, too.

DFR Applications

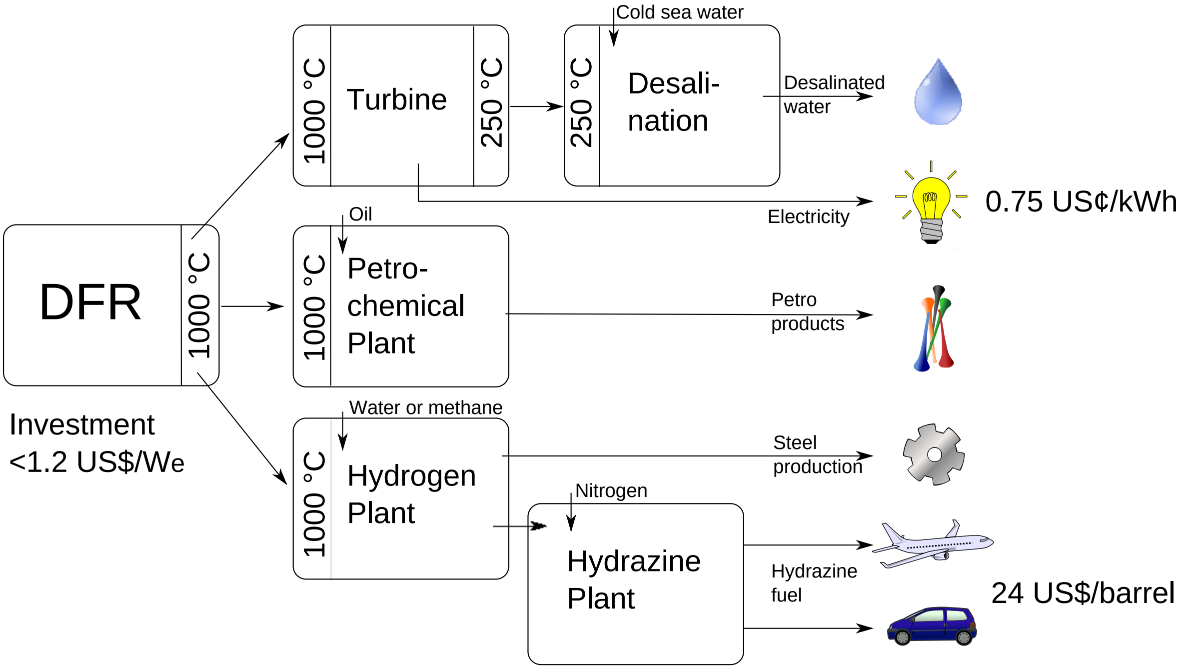

Figure 3. Applications of the Dual Fluid Reactor

The heat can be used to provide electricity with an efficiency of 50% or higher. The gas turbine outlet temperature is still high enough to drive processes like water desalination on a large scale as it is desired in many desert countries. Alternatively, the high temperature can be used for the production of petrochemical products, an essential part of the modern chemical industry, more cost-effectively.

Most interesting is the production of hydrogen, the base material for many chemical procedures. Current steam reforming and similar processes are CO_2 intense and consume fossil fuels. At the high temperature of the DFR, hydrogen can be produced from water by high-temperature catalytic thermolysis at high efficiency. Ammonia and synthetic fuels like hydrazine can therefore be produced completely CO_2 neutral. Energy density and chemical toxicity of hydrazine are similar to gasoline [1], though with the DFR it can be produced for 1/3 of the current pre-tax gasoline market price.

Low hydrogen costs also make the hydrogen reduction of iron for steel production very attractive. Replacing the coke reduction reduces the CO_2 footprint of the steel industry remarkably.

Automotive fuel production

With respect to the high and conceivably rising costs of natural gas and petroleum the nuclear synthesis of fuel is a worthwhile business proposition, especially since it can end the dependency on producer countries in a timely manner.

These synthesis processes are well-tested in chemical engineering. However, they are not very energy efficient. Thus, for the past several years more sophisticated processes have been being developped to achieve significant improvements in this respect. In particular, researching catalysts leads to substantial efficiency enhancements. Thus, ruthenium for example can increase the efficiency of the Haber-Bosch process for nitrogen fixation considerably. The required reactant hydrogen peroxide for the alternative hydrazine synthesis of the Pechiney-Ugine-Kuhlmann process can be produced with higher energy efficiency via the NxCat process. Also for a hydrazine fuel production these developments will lead to a reduction in costs.

A recently developed new method, the "Solid-State Ammonia Synthesis" SSAS, bypasses the hydrogen production and synthezises ammonia directly from water and nitrogen. This would reduce the capital and maintenance costs by a factor of 3, and the energetic production costs by 25%, therefore further halving the total ammonia production costs. SSAS has not yet been applied on a large scale but it provides interesting prospects, in particular when combined with the DFR.

Synthetic Fuels

The operating temperature of 1000 °C provides for the highly efficient production of hydrogen from water through combined electrolysis and thermal decomposition. Such a process, the HOT ELLY process, was developped for the high-temperature reactor at the Jülich Research Center in Germany. Alternatively, the sulfur-iodine cycle process produces hydrogen employing only thermal energy of >830 °C. Hydrogen gas, even highly compressed or cryogenic liquid, has a low energy content and is difficult to handle. Moreover, both processes utilize a significant amount of the energy content of the hydrogen, that cannot be regained. Hence, hydrogen as a fuel for vehicles or aircraft is impractical. Therefore, it seems to be more useful to concentrate the hydrogen in fluid chemical compounds, that are easy to handle.

These synthetic fuels are also known as XtL-fuels, where the substance 'X' is converted *to Liquid*.

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[1] Pure hydrazine has half of the energy density of gasoline. However, contrary to gasoline it mixes well with water which boosts the efficiency in combustion engines while reducing the toxicity and flammability.

The relevant industrial scale synthesis processes are well-developped and used commercially - mainly for chemical engineering in the primary production. They all have in common, that these synthesized fuels made from fossil fuels are obviously wasteful compared to petroleum products. Therefore, they are only used for special applications (rocket propellant) or if the absolute rule of the state takes priority. With the use of 'renewable' energy this becomes completely uneconomical. The situation changes, if nuclear thermal energy is utilized.

Nuclear thermal energy combined with the previously generated hydrogen allows to hydrogenate coal via the Bergius process, by which synthetic benzine or diesel could be formed. (CtL-fuel: *Coal to Liquid*). Instead of hydrogen, the Fischer-Tropsch process may employ syngas.

Hydrazine

If the exploitation of coal is to be avoided, because it is not available or the generation of carbon dioxide is not wished-for, atmospheric nitrogen may be used instead of carbon. Here, the synthetic fuel of choice would be hydrazine (N_2H_4), a liquid fuel with similar properties to benzine (including toxicity). Hydrazine has been used as a rocket propellant for 80 years. Produced by nuclear energy it becomes an affordable alternative to petroleum products for the use in transport. As liquid fuel it can be combusted in piston engines of vehicles and in turbines of aircraft with only minor modification. These adaptions are similar to those for other alternative fuels and affect mostly the quantities of injected fuel and the ignition points. Here, the combustion is a very clean process producing water and nitrogen. Similar to the combustion in air, the production of nitric oxides only depends on the temperature. Hydrazine congeals at freezing temperature, which can easily be avoided by seasonal admixture of antifreezes, such as methylhydrazines or alkanols. In contrast to benzine, it decomposes quickly, if being released into the environment perhaps by accident. In fuel value it is equivalent to LPG (liquefied petroleum gas) and half as much as benzine. This disadvantage in fuel value can be compensated by simply admixing water, since heat engines depend on the difference in pressure and not on the temperature. By adding water the energy content of a fuel can be utilized more efficiently, because the vaporization of the water increases the pressure. This has been tested in the past, but never converted into commercial application, because benzine doesnt't mix with water, thus an additional tank for the water would have been required. In contrary, hydrazine smoothly blends with water, which in addition simplifies the ease of use. Thus, hydrazine may be considered an NtL-fuel: *Nitrogen to Liquid*.

With hydrazine, fuel cells may be produced at a lower price and be operated more efficiently than with hydrogen, because the power density and the level of efficiency are significantly higher, and no rare, expensive metals such as platinum for hydrogen fuel cells are needed for their production. In the past, hydrazine fuel cells have already been used successfully in spacecraft.

Taking nuclear produced hydrogen combined with atmospheric nitrogen and further nuclear energy ammonia is produced via the Haber-Bosch-process. Being the most important precursor in nitrogen chemistry today, ammonia is mainly used for the production of fertilizers. Today, more than 130 million tons of ammonia are produced via the Haber-Bosch-process, already consuming 1.4% of the global fossil energy sources. In this prospering market nuclear produced ammonia may provide a cost advantage, too. Among other things, it can be used for the production of hydrazine via the Olin Raschig process. The additional energy required for the production of hydrazine is released to a great extent in the combustion, as are the reactants water and nitrogen, thus the process may be regarded as a sustainable closed loop.

Pure ammonia itself does not burn in air under normal conditions because the flame temperature is lower than the ignition temperature. However, under certain conditions it may serve as a fuel. These are present in Diesel engines and in turbines with very high compression ratios. The advantage is the lower production cost of ammonia in comparison to hydrazine. Disadvantages include: Ammonia is a gas and can be liquefied under pressure having similar physical properties like LPG hence likewise requiring a pressurized gas tank. The fuel value is somewhat lower than hydrazine but due to the difficult flammability the efficiency boost by water admixture is hardly possible. The utilization of pure ammonia in Otto engines is not possible albeit a mix with hydrazine may work.

Silane

Silane is another synthetic fuel. Silanes are the silicon homologues to carbon-based alkanes. Like hydrazine they are produced endothermically, thus being capable of re-emitting part of the synthesis energy during the combustion. They are characterized by very high energy densities. Starting with heptasilane (Si_7H_{16}) they are stable and easy to handle. Heptasilane is liquid from -30 to 227 °C. It is produced from the reactants water and silicon dioxide (silica) via the Müller-Rochow synthesis, which can be performed at lower cost with nuclear energy from the DFR system. Water and silica re-emerge by the combustion. At combustion temperatures above 1,400 °C silane burns exothermically with atmospheric nitrogen to water and silicon nitride (Si_3N_4). The combustion products silicon dioxide and silicon nitride are solids. This is a substantial problem for conventional piston engines and turbines. Because of its high energy content it is perfectly suitable for ramjets at hypersonic speeds (RAM - SCRAM Jets) and spacecraft engines. Modified Wankel engines and external combustion turbines would allow to use silane in vehicles as well. Thus, silane would be a StL-fuel: *Silicon to Liquid.*

Estimation of Costs

The Dual Fluid Reactor can be used for electricity, automotive fuel production, and heating. The only primary resources needed are naturally occuring fissionable materials, i.e. Uranium and Thorium.

Fission of the uranium nucleus results in an energy release 100 million times more than chemical burning of the atom, for example carbon. Thus, 1 kg of uranium has an energy content of 2,700 tons of hard coal. Present light water reactors use barely 1% of the energy content of natural uranium, thorium is not used at all. Already with today's nuclear power plants the fuel costs make up only a fraction of the operating costs.

For the DFR the exploitation is about 100 times as much, so that even higher fuel costs by a factor of 100 are acceptable, which would allow to continue the exploitation down to regions of average concentration within the Earth's crust. The concentration within granite rock, which is available in abundance, is about 10 to 20 ppm, which in addition correlates with the average concentration of thorium. Uranium deposits with higher concentration were also discovered at the bottom of the oceans. The Japanese method for the recovery of dissolved uranium from seawater is to cost several hundred US$ per kilogram.

In this manner with the DFR system every country can establish an economic autarkic complete energy supply for millions of years.

Electricity production with the DFR

In the following, all estimations relate to the costs of a batch production. The construction of a test facility and a prototype plant which includes licensing procedures will have expenses several times those of a batch produced plant.

The challenge in the construction of a power reactor is to guarantee a negative temperature coefficient under all circumstances to avoid criticality accidents (Chernobyl) and to ensure the removal of the residual decay heat (Harrisburg, Fukushima). This includes limiting the consequences of an accident to the inside of the reactor building by an appropriately sturdy containment.

With the DFR operating under normal pressure special safeguards such as an excess pressure containment can be pared down without compromising safety. Similar to all other modern types of reactors the DFR has a negative temperature coefficient. Continious removal of fission products avoids a build-up of them as is common in solid fuel elements, thus significantly reducing the production of residual decay heat. The cooling system operates so effectively, that the passive removal of residual decay heat is guaranteed and redundant cooling circuits and emergency cooling systems are unnecessary. All in all, this leads to substantial simplifications and reductions in the building's construction, which significantly reduce the building costs per amount of power compared to other types of reactors.

Construction Costs

The impact of the simplifications of the DFR system will be estimated quantitatively in the following. This will lead to a conservative assessment for a serially produced reactor based on experience from plant engineering and construction:

Item	500 MW$_e$ DFR	1500 MW$_e$ DFR
Concrete containment for reactor, earthquake-proof	100	130
Reactor with primary circuit, features including a facility for pyrochemistry	250	300
Secondary loop, heat exchanger*	60	150
Supercritical water turbine 500 MW$_e$ (3x), generator, transformer*	200	580
Tertiary cooling system with cooling tower	140	250
Additional bunkers	100	200
Planning and building authority, contingency	130	200
Sum	**1000**	**1800**
Costs per installed power	**2 US$ / W**	**1.2 US$ / W**

Table 1. Construction costs in million US$

*For the future gas cooling option, the heat exchangers cost less (about 30/70 millions) and the turbines a bit more (250/650 million) compared to the given values in the table. Therefore the sum remains unchanged.

A closed working gas loop with a tertiary cooling system was assumed. Chosing an open air operated loop, the tertiary cooling system can be omitted, which reduces the costs by 10%.

The capital costs of the DFR are comparable to those of a coal-fired power station. They are far below the capital costs for a modern nuclear power plant, which are of the order of for example 3.3 US$ / W_e for the EPR. Scaling for the number of simultaniously built blocks as well as for the size of the reactor a further reduction in costs is achievable. Because no pressure tanks are necessary, it is technically easy to increase the power while the building costs would rise logarithmically. The technology of the reactor also allows to substitute expensive turbines in the conventional section by modern techniques for electricity generation, thus additionally reducing the costs in the further development.

Hence, the operating company does not have to balance high capital vs. low fuel costs for a nuclear power plant compared with a coal-fired power station, where the situation is the opposite, with the nuclear power plant starting to profit from the gains not before 20 to 30 years.

Operating Costs

Assuming a service life of 50 years the annual operating costs are composed as follows:

Item	500 MW_e DFR	1500 MW_e DFR
Operating personnel: 30 man-years (3 shifts 10/12 man-years each 130,000 US$)	4	5
Operating supplies	1.5	2.5
Nuclear fuel: 400 (1200) kg (300 US$ mining, 300 US$ transport, 600 US$ per kg waste management)	0.5	1.5
Maintenance, conventional section (2.5% building costs per annum)	9.5	25
Maintenance, nuclear and pyrochemical section (2% building costs per annum)	5	7
Reserve for decommissioning (25% of the building cost of 1000/1900 million US$)	5	9
Administration, safety	2.5	4
Sum	**26**	**54**

Table 2. Annual operating costs in million US$

Total electricity production costs

Based on an annual average of 8,000 full-load hours, which corresponds to an operational availability of 90%, the electricity production results in 4,000 million kWh at a production cost of

0.56 ¢ / kWh. Here, the fuel costs have a share of 0.0165 ¢ / kWh, even when assuming an uranium price of 330 US$ / kg. Depending on the configuration, the capital costs sum up to 0.43 to 0.50 ¢ / kWh. Thus, the production costs add up to a total of 1.00 to 1.05 ¢ / kWh with the fuel costs contributing ~1.6%.

Item	**500 MW_e DFR**	**1500 MW_e DFR**
Capital costs	0.50	0.30
Operating costs	0.65	0.45
Sum	**1.15**	**0.75**

Table 3. Total costs for electricity produced with the DFR in US¢ / kWh

Already with the small 500 MW_e plant the electricity production costs are only 30% of the costs of a light water reactor or a coal-fired power station. They further decrease to 20% for the 1500 MW_e DFR. The DFR output power can be scaled up much more easily contrary to pressurized water reactors due to their size-limited pressure vessels.

Automotive fuel production with the DFR

The high temperature of the DFR makes a very efficient production of propellants possible. This can be a direct production of synthetic fuels but also support for heat-intensive oil extraction, e.g. from oil sands. In the following, cost savings for hydrazine, ammonia, and DFR-aided oil extraction are compared.

Hydrazine costs

Hydrogen is the base input material needed. Conventional facilities burn natural gas to produce hydrogen while the DFR can produce it directly from water. From hydrogen, hydrazine is produced in two steps. These steps and their corresponding facility costs per kilogram hydrazine are

- Ammonia from hydrogen via the Haber-Bosch process: 6 to 8 US¢ / kg [2]
- Hydrazine from ammonia via the Olin-Raschig process: 6 US¢ / kg (100,000 ton/year plant with 35 years lifetime[3])

The sum is 11-13 US¢ / kg. However, the synergistic and scaling effects reduce it to **8 US¢ / kg**. That synergistic and scaling effects are so large can be seen from typical (10 million tons annual output) petroleum refineries[4] which are far more complex than the hydrazine production facility.

Apart from facility costs, additional costs for energy is needed. The energy input for the production of 1kg hydrazine combines as follows:

- Haber-Bosch process based on water and atmospheric nitrogen (including hydrogen production): 11 kWh_{th}[5] (high temperature)

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[2] "A feasibility study of implementing an Ammonia Economy", Jeffrey R. Bartels, Michael B. Pate, PhD; Iowa State University (2008). www.energy.iastate.edu

[3] "Techno-Economic Analysis of Hydrazine Hydrate Technologies", Punna Nikhitha, Koneru, B. S. Saibabu (2010) onlinelibrary.wiley.com

[4] See www.eia.gov

[5] "PRODUCTION OF AMMONIA", European Fertilizer Manufacturers' Association (2000), page 22. www.diquima.upm.es

- Olin Raschig or Bayer Ketazine process: 2 to 3 kWh$_{th}$, mainly due to hydrazine hydrate distillation, and 6 to 7 kWh$_{e}$[6738] for NaOCl production (electrolysis of brine)

Those needs can be matched by a 3,000 MW$_{th}$ DFR with turbines producing 800 MW$_{el}$. The overall costs of such a DFR system would be 10% cheaper than the 1,500 MW$_{el}$ DFR mentioned in the preceeding section because it needs less turbine power but has the same total thermal power, leading to energy costs of 0.5 US¢ / kWh$_{el}$ and 0.22 US¢ / kWh$_{th}$. The hydrazine output of such a DFR would be about 3,000 tons per day at 90% load. The resulting energy costs for hydrazine production are **7 US¢ / kg**.

Both, the energy costs and facility costs add up to **15 US¢ / kg**, and, not considering synergistic effects, up to 21 US¢ / kg. For smaller plants the price could rise as high as nearly 20 US¢ / kg. A similar calculation for the new SSAS process leads to total costs of 11 US¢ / kg and 17 US¢ / kg without synergetics, respectively.

Comparison with costs for conventional fuel production

The hydrazine production costs can now be compared with conventional fuel extraction and production costs. The following table shows crude oil costs using different extraction methods as well as production costs for gas and coal liquefaction evaluated 2008[9].

Method	Costs US$ / barrel	Costs US¢ / kg[a]
Natural/Artificial lift	10 - 40	8 - 35
Deep / ultra-deep-water oil fields	30 - 65	25 - 55
Heavy oil/bitumen	20 - 70	15 - 60
Steam/Gas injection (oil sands)	30 - 80	25 - 65
Oil/tar shale extraction	50 - 110	40 - 90
Gas to liquids	40 - 110	35 - 90
Coal to liquids	60 - 120	50 - 100

Table 4. Conventional oil production costs

For refinery, additional cost of 6 ¢ / kg (8 $ / barrel) must be added.

The energy costs contribution is not negligible and depends on the method by which the oil is extracted. For refined oil from the Middle East it is only 2 ¢ / kg [10] but for the energy intense oil sand extraction in Canada (in-situ SAGD process with suceeding hydro cracking) it contributes with remarkable 7-8 ¢ / kg. Here the DFR can reduce the costs significantly by providing heat and electricity at extremely low costs.

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[6] See www.sciencemadness.org

[7] Chlor-Alkali-Elektrolyse – kostengünstig mit optimierter Membrantechnologie www.cac-chem.de

[8] "Low-Cost Precursors to Novel Hydrogen Storage Materials", Suzanne W. Linehan et al. (2010), pp. 82-84. www.osti.gov

[9] IEA World Energy Outlook 2008, p. 218 ff. www.iea.org

[10] "Energy and Environmental Profile of the U.S. Petroleum Refining Industry", U.S. Department of Energy (2007), assumed 0.06 US$ / kWh electricity and 0.012 $ / kWh for natural gas. www1.eere.energy.gov

The energy cost savings become extreme when producing synthetic fuels. With conventional methods the ammonia and hydrazine production is dominated by 70-80% energy costs and therefore can not compete even with gasoline. This changes dramatically when using the DFR. Hydrazine and ammonia can now even compete with Middle East oil. The following table shows overnight costs for some fuel production processes, both for with conventional energy supply and DFR energy supply. A fuel-producing DFR facility unites all processing steps in one unit causing lower labor and capital costs, compared to the conventional production lines.

Method	**Total costs US¢ / kg**[a]		**Total costs US¢ / MJ**[b]	
	conventional	**DFR**	**conventional**	**DFR**
Refined oil from Middle East	11 - 13	10 - 12	0.27 - 0.31	0.25 - 0.29
Refined oil from oil sands, Canada[cd]	31 - 42	27 - 37	0.75 - 1	0.6 - 0.9
Hydrazine production	~44	**15 - 21**	2.4	**0.8 - 1.1**
Hydrazine production, SSAS	~37	**11 - 17**	2.0	**0.6 - 0.95**
Ammonia production	22	8	1.3	0.45
Ammonia production, SSAS	15	4 - 5	0.8	0.25

[a] 1 barrel (~159 l) of light oil/gasoline and hydrazine has a mass of about 120 kg and 160 kg, respectively.

[b] The lower heating value of oil-based fuels, hydrazine and ammonia are ~42 MJ/kg, 19 MJ/kg and 18 MJ/kg, respectively.

[c] OIL SANDS TECHNOLOGY ROAD MAP, UNLOCKING THE POTENTIAL, JANUARY 30, 2004, Alberta Chamber of Resources. www.acr-alberta.com

[d] Third Quarter Report 2011, Canadian Oil Sands Limited. www.cdnoilsands.com

Table 5. Fuel production costs, conventional and with the DFR (3,000 MW_{th} systems)

It is stressed again that hydrazine can be used in vehicles with higher efficiency when mixed with water compared with gasoline which does not mix with water. Therefore, the hydrazine costs related to the mechanical energy (or to the distance driven by a vehicle) are a factor of 1.5-2 lower than the per-energy costs. On a per-energy basis, the hydrazine-producing DFR facility can compete with oil production costs equal to or higher than 40 US$ per barrel (including refining), so only conventional oil sources on land are cheaper. 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 with hydrazine from the DFR facility. These resources are expected to be exhausted first and soon[9].

Reflections on the Market

An assessment of the need for nuclear power plants results from an overview on the present energy market.

The annual energy consumption in Germany is as follows: 1,300 million MWh mineral oil, 850 million MWh natural gas and coal, 600 million MWh electricity.

Per-capita consumption: 16 MWh mineral oil, 10 MWh natural gas and coal, 7.5 MWh electricity.

This can be converted into the number of DFR plants necessary to produce the same amount of electricity and nuclear energy for the production of fuel. Here, the assumed size of the plant is the some 3 GW_{th} reference we used here before. The fuel market could be transfered quickly and profitably to nuclear synthesis by successive expansion. In the case of electricity plants, a lot of old sites are due for shut down, which results in a need for additional sites. For the complete fulfillment of demand 80 plants would be necessary for the generation of electricity and about 90 nuclear plants for the production of fuel, including the recovery of waste heat and variations.

The world wide consumption ranges at 22,000 million MWh of electricity and 84,000 million MWh of fuels and heating, respectively.

With respect to the increase in standard of living in emerging countries forecasts expect these numbers to double until 2050, corresponding to a need of 3,500 DFRs for electricity and at least 6,500 DFRs for the production of fuel and heating. This compares to the number of old sites, that need to be replaced (today 80% of all existing plants) and fossil fuels, that need to be subsituted for.

Today a power plant capacity of 750 GW for the production of electricity is available within Europe. Of this 475 GW will already need to be replaced by 2020 due to aging of facilities.

Forecasts on the price for fossil fuels on the world market expect only little increase for coal until 2050. However, the prices for mineral oil and natural gas are expected to rise significantly. This is less a result of a shortage in supply, but rather based on the fact, that the means of exploitation for available deposits become more costly. The nuclear synthesis of XtL-fuels will become a continually growing market.

Comparision of Productivity in Power Plant Technology

The deployment of new power plants, such as the DFR system, can be seen in the context of the general economical and political situation. However, with rational contemplation the choice for a technology of energy generation is guided mainly by physical measures, which leads by itself to economical productivity.

At first, the term *energy production* should be specified. In consequence of the conservation of energy law, energy can neither be produced nor nor destroyed, but is merely transduced from one form into another. A **power plant** produces *exergy*, that fraction of energy, that is available for mechanical work. The electric energy produced by a power plant from the employed primary energy is pure exergy, since it can be completely utilized for mechanical work or converted into any other form of energy. The unusable fraction called *anergy* remains and is dissipated at low temperature as heat. Therefore, with respect to the primary energy, every exergy production has an efficiency of < 1.

ERoEI

The economical productivity of a power plant is rated by the ERoEI. The ERoEI or ERoI is the energy returned on the energy invested (or energy return on investment). It is the quotient of the sum of exergy produced by a power plant during its service life and that exergy, in this case actual work, that is needed for its construction, operation (including procurement of fuel) and waste management. A power plant has to have an ERoEI significantly bigger than 1, otherwise the invested effort does not pay off. In the economical process a power plant is the more productive the higher the ERoEI. For a low ERoEI the effort is wasted.

In the following, the ERoEIs for different types of power plant technologies are compared.

Power plant technology	ERoEI
Pressurized water reactor[a]	80
Run-of-the-river hydroelectricity	36
Black-coal fired power	29
Gas-steam power	28
Solar thermal (desert)[b]	9
Wind power (german coast)[c]	4
Photovoltaics (desert)[b]	2.3
DFR (500 MW_e)	**1200**
DFR (1500 MW_e)	**2000**

[a] This value is calculated using the today's enrichment technology and mix. Earlier values are lower because of energy intense diffusion enrichment.

[b] The ERoEI for solar energy includes pumped-storage hydroelectricity, which is energetically most favourable, to balance day-night fluctuations (factor 2). This storage is unlikely to be applicable in the desert and has to be replaced by other storage means, further reducing the ERoEI. Damages by sandstorms are also not included in the ERoEI.

[c] The ERoEI includes over capacity needed to provide supply for seasonally weak periods (factor 2) and pumped-storage hydroelectricity to balance short-term fluctuations (factor 2). Without those facilities, the ERoEI for wind at the german coast would be 16.

Table 6. ERoEIs for different electricity generating technologies

The so-called renewable sources of energy (energy is not renewed, especially not exergy) have low ERoEIs and employ the spent exergy inefficiently, thus not sustainably. They are characterized by a very high exergy input for the construction of the plants and high maintenance with relatively short service lifes, except for hydroelectric dams. Since electricity cannot be stored, a power plant must produce the electricity on demand. The 'renewables' are incapable of that and need means to store the untimely produced exergy by conversion to other forms of storable energy. The exergy expenses for these storage facilities enter the denominator of the ERoEI thus reducing it considerably. Growing experience with environmental inclemencies, increasing maintenance expenses, and/or shortening service life are not yet considered and would further reduce the ERoEI significantly. So the values for the 'renewables' as given in the table pose upper limits.

Monetary aspects

The monetary return on investment factor is usually lower than the ERoEI because deviating market prices and different personnel expenses reduce the value albeit there is a proportionality. Empirically, the value of the ERoEI must be greater than 5 to gain profit.

So the ERoEI determines the energy generation costs. In an economic region the energy price is determined by the ERoEI of the prevailing power plant technology. If the power technology is changed the quotient of the energy prices before and after the change are equal to the inverse of the quotient of the correspondent ERoEI's. During the transition, energy generation costs of the 'new' power plants are still dominated by the 'old' power technology since the 'new' power plants are constructed with energy from the 'old' power technology. If a change from fossil power to solar power is be done the quotient of the ERoEI's is about 0.1. The energy price will be 10-fold after the change is accomplished. Meanwhile the solar energy price is considerably lower (although increasing) because of the subsidization by fossil power. Conversely, while changing to the DFR technology the DFR energy price is increased by fossil power though finally decreasing below one tenth.

Development Potential

For the development of the DFR the setup of a modular testing facility would be appropriate. In this facility the stepwise construction of the DFR could be realized. Most development steps also provide vertices for a commercialization branch.

The first step would be the construction of the reactor with a once trough fuel cycle and a heat exchanger to a supercritical water cycle in order to dispose of the heat to a cooling tower or a river.

The dimensioning of the reactor would be about 1 GW_th. In principal it is possible to build a small low powered fast reactor. However the concentration of fissile material would than rise to at least 90% for a thermal power of about 1 MW or less. It is then no longer possible to use plutonium as fissile material because the temperature coefficient due to Doppler broadening of resonance capture is insufficient in order to retain a negative temperature coefficient. Instead highly enriched uranium-235 is required, which would be weapons-grade in contrast to reactor plutonium. A small fast reactor with a plutonium concentration of up to 35% could be constructed with a thermal power below 100 MW down to several 10 MW. With rising size and power level of the reactor the necessary plutonium concentration decreases.

In this first step the principal functioning and the self-regulation features of the reactor are demonstrated.

In the second step a pyrochemical processing unit is connected to the internal fuel cycle of the reactor. Both options of the PPU implementation should be tested, i.e. rectification and electro refining. At this stage the nuclear part is up and running as specified.

A plant derived therefrom can already be put on the market as a transmuter to annihilate waste of current nuclear power plants. If a turbine is introduced in the supercritical water cycle a first power plant can be tendered.

The third step is the construction of a prototype power plant representing the reference system with a supercritical water turbo-generator. Specialized heat exchangers for heat transduction to chemical plants may be developed with possible connected prototype plants for hydrogen, ammonia production or petrochemical processing. The further development steps lead beyond.

A further step could comprise the installation of a noble gas turbine with a direct contact heat exchanger from the liquid metal coolant to the noble gas in the secondary loop. The particular coolant loop intertwine allows for a predetermined innovative leap in the heat exchanger technology which increases the efficiency considerably.

The liquid metal coolant due to its high charge carrier concentration allows for the effective deployment of magneto-hydrodynamic generators which has no moving parts and would be low in maintenance and costs in comparison to gas turbines. A similar advantageous option is the AMTEC generator. The adapted development may result in combined systems increasing the electric efficiency and economy.

The nuclear part of the DFR so far uses actinide halogenides as liquid fuel. The concept, however, alternatively allows for a molten metal alloy. This would enable further advantages. Due to the high heat transportation capability of metals and lower corrosion potential in comparison to molten salt it is possible to further increase the power density -- reducing the size of the core accordingly -- and increase the operating temperature yielding a significantly higher electric efficiency and ERoEI. A second test reactor core may be constructed with metal alloy fuel and an adapted PPU. The metal alloy fuel consists of the actinides and metals with low melting points such as lead, bismuth, tin which result in an alloy with a low solidus temperature analogue to a solder rendering it pumpable.

All along this straight line of development the DFR exposes itself as a power plant technology where the portion of the cumulated exergy expense in the ERoEI pertaining to the DFR and its operation itself is decreasingly small in comparison to the exergy expense for the retrieval of the fissionable material. Since the ERoEI is then limited by the mining operations this means that the DFR exhausts the potential of nuclear fission resulting in an ERoEI two orders of magnitude higher than all conventional power plant technologies including fuel from newly developed resources like shale gas and shale oil and future resources like methane clathrate from the bottom of the oceans. It can therefore greatly outperform generation III+ and generation IV plants which are losing competition with the aforementioned new fossil resources.

Environmental Issues

Human economy effectuates large-scale use and refactoring of landscape and natural habitats. The higher the efficiency of the economy the lower the impact on the environment. The highest impact comes from agriculture, followed by the energy industry. They both experienced a remarkable efficiency gain in the past 200 years. However, production and use of energy for electricity, transportation, heating/cooling, industrial, and commercial purposes have varying degrees of impact on our environment, and in recent years, the relationship between these energy sources and their impact on the environment has taken center stage. Determining the net cost-benefit of the various energy sources, and in particular their impact on the environment, is a very complex puzzle. One part of that puzzle is how the production and use of the energy sources affects the earth's climates and those that live in those climates.

In assessing the effect on the environment of any particular source of energy one needs to consider the entire process of extracting, converting and housing the particular energy source.

Most sources of energy we use on Earth are produced by the Sun’s energy, whether it is oil, natural gas, coal, wood, hydropower, wind, photovoltaics and solarthermal. Nuclear, geothermal, and tide are not based on the Sun’s energy. The following is a very brief summary of which types of energy sources provide us with the most amount of energy for the least amount of negative impact on the environment, i.e. which one has the highest efficiency. The various energy sources, examined below, are categorized as fossil fuels, so-called "renewable" energies and nuclear energy.

Fossil Fuels

All fossil fuels (oil, natural gas, coal) when converted to electricity, heat, or gasoline, produce the so called “greenhouse gases”, which is mainly carbon dioxide (CO_2). It is a wide-spread assumption that the accumulation of greenhouse gases in the atmosphere may contribute to global warming and climate change. Extracting these fuels, through mining or other methods, produces more greenhouse gases in addition to other pollutants and damage to the landscape. Finally, building facilities to convert fossil fuels to electricity or other forms of energy also produces greenhouse gases and other pollutants. So, greenhouse gases and other pollutants are emitted when fossil fuels are extracted, converted, and when the facilities for these activities are built. It is estimated that by the end of 2009 the emission of greenhouse gases is about 50 billion tons of carbon dioxide equivalent [11].

Coal extraction and consumption not has the largest CO_2 footprint but also when burned, coal emits Radon and Uranium, and in some cases Thorium into the atmosphere. These radioactive materials do exist naturally in the soil that contains the coal.

The mining of fossil fuels, especially coal, takes the overwhelming share of mining activities, diminishing mineral mining (including uranium) with ensuing destruction of natural habitats.

Fossile fuels were built up by the Sun over millions of years and are now being consumed within hundreds to thousands of years, so the consumption speed is a factor of 10,000 faster than production. That's why fossil fuels can not be considered as a sustainable energy source on a long-term scale.

"Renewable" Energies

Energy or resources consumed by a power plant are never renewable but this term has been established for the use of energy from naturally running power sources like the Sun, Earth's internal heat (geothermal) or energy from orbs constellations (tide). This energy source must not be consumed faster than its (re)generation at any time. "Renewables" means essentially photovoltaics, concentrated solar power CSP (both driven directly by the Sun's radiation), wind and hydro energy (driven indirectly by the Sun).

Energy must be converted to electricity or mechanical energy in order to be useful. It is a physical fact that this conversion is more efficient with higher energy density. The energy produced by the Sun in one second is enough to last us on Earth for about one million years based on world energy consumption in 2010. This energy, however, is radiated almost uniformly over the entire surface of the Sun, so most of the energy is lost into space. Only 0.00000005% of the Sun's energy reach the Earth, resulting in a constant irradiation of 1,400 Watt per square meter (W/m?) at the upper atmosphere[12]. During the night the solar radiation is zero, so the average value is half of it. This is further reduced by another factor of 2 when the light travels through the atmosphere, and by another factor of 2 in areas with a latitude of middle Europe or the USA. At these latitudes the usable average Sun energy is only 200 W/m?.

This energy density is very low for technologies that convert it to electricity. However, it becomes useful when natural processes concentrate the energy. This happens when the Sun drives water on mountains where it flows down in rivers, or when the Sun produces regions of high atmospheric pressure resulting in wind. Therefore, from the "renewables", hydro and wind power have the highest ERoEIs (see above). Hydroenergy has the additional advantage that day/night and other fluctuations are essentially balanced, so it can provide a stable and continuous energy supply. Wind energy is extremely unstable so that huge storage facilities are needed. This undermines the advantage of a natural concentration of the solar energy in wind.

Photovoltaics is the attempt to convert the Sun's radiation energy into electrical energy *without concentration*. The missing concentration makes this technology extremely ineffective and brings it to

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[11] UNEP 2011. Bridging the Emissions Gap. United Nations Environment Programme (UNEP): www.unep.org

[12] The Sun's total power is 400 trillion TW (Terawatt). However, this power is emitted over the Sun's surface of 6,000,000 trillion m?, so that the radiation density is 70 MW/m?. Since the Earth is 150 million km away this number is reduced by factor of 50,000 which results in an 1400 W/m? at the upper atmosphere, the so-called solar constant. Summed over the Earth' surface this is a power of 200,000 TW, or 15,000 times the world's energy demand.

the bottom of the ERoEI list. A large-scale use of photovoltaics is only possible with Silicon-based technology. For other technologies like CIS there are not even sufficient materials on Earth to use it on a large scale. The efficiency of installed photovoltaics including shading effects and conversion losses is 10%, so only 20 W/m? is the actual electricity output, in southern countries up to 40 W/m?.

Concentrated solar power (CSP) is a technical solution where the power density is increased before converted into electricity in order to gain higher efficiency. Since there is a non-linear dependence on the solar irradiation these plants can only be operated in desert contries with a useful electricity output. The ERoEI can be remarkably high but this is also reduced by needed day/night storage facilities and the requirement of long-distance power transportation.

Biomass is another application. Here, biological processes are used to concentrate the solar power. Since the combined efficiency for photosynthesis which stores the energy in the plants and the electricity generation is barely 1% the area consumption is the largest of all "renewable" energies. Even though no storage is needed the ERoEI is in the same region as photovoltaics.

The most important character of an energy source is not the total amount of energy it contains but its energy density, that is, the energy/unit volume, or energy/unit mass, or energy/unit area. Low energy density has a twofold disadvantage. It consumes large areas (which maximizes the footprint and impact on the environment) and it produces the electricity very inefficiently. The main difficulty with renewable energies is that they are of very low energy density, except for hydropower. To demonstrate this point, let us consider the Bluewater Power Station in Perth, Australia. This power station uses coal to produce about 460 MW of electricity. It consumes about 3.2 million tons of coal every year. The footprint of the Bluewater power station is 145 hectares or 1.5 million m?, which means that this power station has power density of about 300 W/m? compared to 20 W/m? for photovoltaics.

The production of an appreciable amount energy using renewable sources is hampered by the low energy density and fluctuations during the day and the seasons and due to weather conditions. Overcoming these hurdles leads to some environmental problems. The low density requires the use of hundreds or even thousand of solar panels or wind turbines occupying huge amount of land. Solar panels need to be kept clean and rotated in order to follow the Sun to collect the maximum amount of the Sunlight and that requires the use of motors that consume part of the energy generated. Rare earth metals are used in manufacturing the solar panels and electric generators for the wind turbines. Rare earth metals are available only from a small number of countries (mainly China) and that will lead to a monopoly that is not unlike the current oil monopoly. Solving the fluctuation problem requires the use of storage devices like electric batteries. Once again, very large number of batteries needs to be used for any reasonable scale solar or wind turbine stations. Eventually those large numbers of solar panels, motors, wind turbines, and batteries need to be decommissioned and buried somewhere. Currently, the manufacturing of solar panels, motors, wind turbines, and batteries uses energy produced by fossil fuels. Finally, manufacturing hundreds or thousands of solar panels, motors, wind turbines, and batteries makes the ratio “energy returned/energy invested” (ERoEI) quite low compared to fossil fuels.

It is unfortunate that all “renewable energy” sources like solar, wind, and tide are low energy density sources and cannot replace the much higher energy density of fossil fuels. Industry and heavily populated areas demand very large and steady supply of energy. Such demand can only be met by high-density energy sources. It is unfortunate because renewable energy sources cause less emissions than fossil fuels. Renewable sources like solar and wind energy are not completely clean and they do have negative impact on the environment due to the large area consumption. However, they might be useful in niche applications. Actually, hydropower is the only "renewable" power source which is roughly as economic as fossil energy sources.

If we stop using fossil fuels in the future, we need to replace them by another high energy density source. Furthermore, oil is a valuable source for petrochemicals or other materials and it would be wise not to burn it for energy.

Nuclear Energy

Any piece of matter is equivalent to energy according to Albert Einstein's famous formula $E = mc^2$ where m is the mass to be converted, E is the energy produced, and c is the speed of light. Theoretically, the current worlds primary energy demand can be met by converting about 6,000 kg of matter to energy every year. Unfortunately, so far, no simple straightforward method of converting matter completely to energy has been found.[13]

Current technology allows only the conversion of a small fraction of the mass into energy. For conventional fuels the mass change is tiny after the chemical energy is released. For instance, black coal has a mass change of 0.00000003% after burned. This gives an idea of the fraction of the energy density we are actually using and how much is left as "waste". Contrary, nuclear fission of uranium results in a mass change of 0.1%. This still seems to be still low but it is 3 million times higher than the energy density of black coal. However, this is the maximum burn-up possible with nuclear reactors. Current reactor types burn barely 1% of the mined uranium, so only 0.001% of the mass is converted to energy, therefore the actual ratio to black coal is 30,000. For nuclear fusion the converted mass is already a few percent but the technology to use it is not yet available. To further demonstrate this ratio let us assume a power station of 1,000 MW electrical output. A nuclear power station of this size needs about 100 tons of Uranium every year while a coal fired power station need about 2 million tons every year[14].

Generation IV fast reactors comes close to the theoretical limit of 3 million times higher energy density than coal while current nuclear technology has "only" a factor of 20,000 higher energy density. The higher energy density of nuclear fuel means an extremely low impact on the environment. Compared with coal and similar fuels this means that

- the land consumption by mining for those resources is reduced by this factor,
- the fuel transportation effort and costs which are quite high for fossil fuels are reduced by this factor,
- the area consumption by the power plants is much smaller related to the energy output, and
- the "death toll" which is fairly high for the coal industry is remarkably reduced.

Since the total amount of nuclear fuel needed for the same electricity output is so small, enrichment as well as recycling of nuclear fuel, even though often discussed as "pollutant", is still extremely small compared with the impact of fossil fuels.

It is often claimed that "nuclear waste" is the main problem of nuclear energy but what are the actual numbers? The nuclear energy is released when the heavy nucleus is split into lighter nuclei. These

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[13] Einsteins formula describes the maximum energy density E/m which is simply c? = 90,000 TJ/kg = 25 TWh/kg.

[14] The electricity output of current nuclear power stations is a bit less efficient since they work at lower temperatures as coal-fired stations, so the ratio of the "electricity densities" is about 20,000.

nuclei are called “fission products” and they can not be used for further energy production. Some of these nuclei are radioactive for a long time and must be treated as waste. Another part of the radioactive waste is coming from heavy nuclei that have been activated by capturing neutrons in the reactor. These so-called actinides can be used in Generation IV reactors since they still carry 99% of the nuclear energy that has not been released. The DFR is an advanced and more economical concept.

A 1,000 MW power plant can supply 1 million people with electricity (including embodied energy, not only the electricity on the personal bill). From the 100 tons natural uranium per year needed 1 ton has been burned in current reactors and therefore ends up in fission products. Per person this is 1 gram per year. *For a lifelong nuclear electricity supply this is only 80 grams waste per person.* Most of these fission products decay in a few ten to 100 years and only 10% require long-term storage of about 100,000 years, so the actual long-lived fission product waste (LLFP) is only 8 grams per person-life. Since these LLFPs decay slowly they have a very low radiotoxicity.

There is no common concept how to treat this waste. Some countries store the used fuel elements as they come from reactors in unused mines, others separate the fission products (80 grams per person-life from which 8 grams are long-lived) and encapsulate them in molten glass (coquilles) for final storage. No final storage facility is in use yet but even from the intermediate storage facilities the chance of any of this waste escaping into the environment is extremely small. It has not happened in all the decades since the beginning of commercial reactor operations in the 1950s. Many radioactive isotopes are useful in medicine and industry. Unfortunately, there are currently very few processing facilities and there are no plans to build more.

During operation a nuclear power plant does not directly emit greenhouse gases into the atmosphere. Some emissions from services around a nuclear power plant are negligible but for the construction of the plant a lot of concrete is needed which has a considerable CO_2 balance. There is no doubt that the total greenhouse gas emissions are negligible compared with fossil fuel based plants but how does it compare with the "renewable" energies?

Taking into account the total lifecyle, a typical wind park like in Dornstedt, Germany, with a power output of 17 GWh per year and a lifetime of 20 years requires 7,200 tons of concrete. A typical reactor like the AP-1000 needs 20 times as much concrete but produces 450 times as much electricity per year. Moreover, the lifetime is at least 40 years (probably much larger), so the concrete consumption related to the electricity output is a factor of 40 smaller.

Again, the higher energy density is the dominating factor. For non-fossil power plants, concrete is the main greenhouse gas driver and it can be concluded that even wind power has a factor 40 larger carbon footprint than nuclear power. Similar conclusions can be drawn for other resources and other energy sources like solar energy.

Dual Fluid Reactor (DFR)

The main advantages of the DFR are its compactness, low complexity and cost structure wich is reflected in the superb ERoEI. These advantages are achieved by a high power density, profound simplifications made possible by the utilization of basic physical control loops for reactor regulation, and abandonment of a fuel cycle industry. The net ERoEI gain is a factor of 10-20 to contemporary water cooled reactors and another factor of 2 to SFR's

The complete burnup of the fissionable material diminishes the fuel costs of the DFR to insignificance. This means that for the same uranium or thorium mining effort one obtains 100 times the energy. However, the minimg costs are already a small fraction in the cost structure of nuclear power plants. As long as the high grade ore mines last thermal reactors are in better competition to the generation IV breeder reactors.

The reduced size and effort to build and operate the DFR compared with the energy output further reduces the environmental impact. Only a few plants are necessary to provide electricity for an entire country and the plants are almost invisible. The uranium and thorium mining is completely negligible, in fact, stockpiled actinide resources in countries that have already used nuclear power for decades are sufficient for several centuries of operation. Additionally, the high neutron excess of the DFR can be used for transmutation. This means that even the long-lived fission products can be at least partially deactivated which reduces the radioactive waste problem remarkably.

In vehicles, there is currently no alternative to chemical fuels. Electric cars do not provide a solution for long-distance transportation. The main reasons are the low efficiency, the low energy density, and short lifetime of batteries, not to mention logistic problems emerging from long recharging times. Contrary to what is promoted by some companies and politicians, there is no solution of these problems coming into view. Moreover, batteries need large amounts of lithium which has a high environmental impact when extracted.

The high temperature of the DFR makes it possible to replace fossil fuels used for vehicles with synthetic ones for costs at the low end of fossil fuels. Moreover, these fuels can be produced totally CO_2 neutral and do not consume any further resources. Not even the vehicles have to be replaced which is a very economic and environmental-friendly solution. Furthermore, the fuels do not need to be shipped around the world since they can be produced locally. This makes big oil spill catastrophes part of the history.

Frequently Asked Questions

Who says this reactor is working?

Simply spoken if only enough fissile material is stockpiled the pile becomes an operating nuclear reactor. This happens in nature, too (Oklo natural reactor in Gabon, Africa). One can imagine the DFR as a liquid metal cooled fast reactor with just one fixed fuel element. In such a manner the DFR ist very similar to the world wide operated sodium cooled fast reactors. In the SFR an assembly of fuel elements filled with uranium plutonium dioxide pellets is the active core which is cooled with streaming liquid sodium. If the fuel rods are interconnected and filled with uranium plutonium halide instead of the oxide pellets one arrives almost at the DFR. Liquid lead cooled reactors are constructed similar, only exising reactors are much smaller than the sodium cooled types.

Is it a fast reactor?

Yes. Not even this, the neutron spectrum is very hard, thanks to the low moderation properties of lead and the absense of dilution of the fuel. The very hard neutron spectrum is also the reason for the high neutron excess which can be used for breeding, transmutation or isotope production.

What kind of salt is used in the fuel?

Fluorine salts have still have considerable moderating quality thus softening the neutron spectrum and deteriorating the neutron economy. Furthermore, many of the involved metal fluorides have a boiling point too high for an effective online reprocessing in the PPU.

Higher halogens are more practical with respect to both properties. For the metals in the used fuel mixture chlorine salts have sufficiently low boiling points yet still higher than 1000 °C as required in the DFR core.

Isn't the corrosion at 1000 °C a big problem?

No. Most material problems exist for thermal reactors, but since the DFR is a fast reactor, the choice of materials opens widely. In principal the material problems were already solved by the MSRE development. In the past more durable and resistant materials were applied in industry. Those materials are rarer and rather expensive. Indeed they are affordable for the DFR because of the high powered small core and the abandonment of fuel elements the required amounts are low.

How can the molten-salt be reprocessed?

Thanks to the separation of fuel and coolant loop the fuel can be reprocessed online in the PPU. Dry high temperature processing can be used in combination with the fuel cycle. Due to the ionic nature of the bond, the used fuel salt is impervious to radiolysis and as such is directly suitable for physicochemical separation methods at high temperatures.

Two such methods have been proven in the past: the molten salt electrorefining method of the IFR and the high temperature distillation of the MSR. Both can be utilized in the DFR. The capacity of the pyrochemical facility can be designed even much smaller because the processing is performed online continuously. In a simple version, the electrorefining method can be used to purify the fuel salt by precipitation of a fission product mixture. For the purpose of specific transmutation a more precise separation is required which can be accomplished by fractionated distillation / rectification which is beyond the MSR principle.

Thanks to the low boiling points (but still higher than 1000 °C as required in the DFR core) a separation in a fractionated distillation facility alone becomes feasible.

What is the size of the reactor, what is the shape?

The shape of the reactor is a cube because the durable metal alloys for the fuel ducts are harder to process. So unbowed parts are easier to manufacture into the fuel duct assembly. The size of the reactor vessel is approximately 2 m edge length for a power output of 1 GW_{th}.

What is a typical actinide mixture and concentration in the fuel?

Nominally, The fuel consists of undiluted actinide salt. However, the composition of the fuel is very flexible and depends on the particular application. At least enough fissile material (i.e. ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu) needs to be contained in order to keep the reactor critical. Minor Actinides (which are fissionable) may contribute, too. The other fractions are fertile material (i.e. ^{238}U, ^{232}Th) and possibly a small fraction of to be transmuted material like long-lived fission products. A small system with 1 GW_{th} working with U-Pu cycle has a concentration of 35% plutonium and 65% (depleted) uranium. With increasing reactor size the concentration of the fissile material is declines.

What happens with the fission products?

Fission products produce decay heat, the fresher they are, the more. Therefore, they must be stored thin in space to ensure sufficient passive cooling.

In solid-fuel reactors as they are in use today, there is no way to avoid the accumulation of fission products in the fuel rods while the reactor is running. For this reason, active cooling is required, even when the reactor is shut down, depending on the time the reactor was running with those fuel rods. The requirement of active cooling is the biggest safety challenge für solid-fuel driven reactors and lead to the problems known from Harrisburg and Fukushima.

This is totally different for the DFR. Since the liquid fuel circulates through the PPU outside the reactor core, fission products can be continuously separated from the fuel and therefore can not accumulate in the reactor core. Outside the reactor core they can easily be stored according to the usual safety standards for radioactive waste handling. When the DFR is shut down, no active cooling is required.

Furthermore, since the DFR is able to transmute fission products in a very effective manner, medium-lived fission products like ^{90}Sr could also be de-activated in the system which would further reduce the waste storage size. Assessments for these possibilities are in progress.

How proliferation-resistant is the DFR?

Breeding additional pure ^{239}Pu (DFR running in breeder mode) for nuclear weapons is not possible, because there is no seperated breeding zone containing pure ^{238}U. Using a fractional-distillation PPU with the U/Pu fuel cycle, you would have to remove ^{239}Np (half-life about 2 days) very fast. This is hardly possible. Since the DFR's nuclear part is fully enclosed and watched telemetrically by anti-proliferation authorities, there is no way to extract weapons-grade material. Using an electro-refining PPU, makes things even harder for bomb makers, because it can only distinguish between actinide salts and fission product salts. The highly radioactive ^{239}Np must be chemically purified in a separate facility within hours to one day, which is nearly impossible, and because such facilities are not necessary for the civil use of the fuel cycle.

When using the Th/U cycle, the ^{232}U isotope, synthesized via (n,2n) reactions, is generating intense hard gamma radiation, which can be detected easily and causes serious damage to weapon electronics. The fractional-distillation PPU is secured in the same way as it is in the U/Pu cycle, preventing the ^{233}Pa being captured by bomb makers.

Compared to the well-known standard method for bomb making, the enrichment of weapons-grade uranium from natural uranium, both possibilities mentioned above are far more difficult to realize.

Is shale gas power not cheaper than nuclear power?

Cheaper than from the DFR? No way!

Long answer: Gas power plants have the lowest construction effort of all power plant technologies, since it is not much more than a turbine with a generator a turbocompressor and a comparatively tiny combustion chamber directly in front of the turbine. Devices which require most other power plants, too. However the "combustion chambers" of coal plants are much larger and more complex. Similar for a nuclear plant with additional abundant safety equipment. Therefore the investment costs for gas plants are low but the effort to provide the gas is much higher than for coal plants let alone nuclear plants. This is reflected in the ERoEI's which are similar for gas and coal plants and almost 3 times lower than for nuclear power plants.

However ERoEI's are higher than market prize relations. The prizes for natural gas are artificially superelevated by the cartel of the few countries which possess abundant easy extractable gas deposits. Thus gas power plants have the highest production costs of the conventional power plants. (unconventional) shale gas deposits are more even distributed on earth and despite their considerable higher extraction costs they reduce the market price of gas because they break the ascendancy of the cartel. Despite of the even lower ERoEI of a gas plant fueled with shale gas it can be attractive to investors because the investment costs are low and the electricity production costs competitive though higher in comparison to coal plants. This means a shorter financial amortization time than for other power plants. The head start in the ERoEI of PWR plants is diminished by political costs like exuberant licensing procedures.

It is therefore necessary to exploit the vast potential of nuclear fission to a larger extend than existing nuclear technologies. That can be achieved by a high powered reactor core with a overall simplified design and inherently safe and simple operation. Also the costly fuel cycle industry needs to be abandoned. Precisely that is achieved by the DFR with an ERoEI of 1000.

Glossary

DFR: Dual Fluid Reactor.

EPR: European Pressurized Water Reactor, newly rephrased as "Evolutionary Power Reactor"

ERoEI: (ERoI) Energy returned on energy invested.

LFR: Lead-cooled Fast Reactor.

LFTR: Liquid Fluoride Thorium Reactor.

MSR: Molten Salt Reactor.

MSRE: Molten Salt Reactor Experiment.

PPU: PyroProcessing Unit.

SFR: Sodium Fast Reactor.

SAGD: Steam Assisted Gravity Drainage.

SSAS: Solid-State Ammonia Synthesis.

W: Watt (Power, Rate of Energy production/consumption) J/s.

MW: 10^6 W.

GW: 10^9 W.

Wh: Energy produced/consumed in one hour = 3.6 kJ.

MW_{th}: Thermal (heat) Power production in a nuclear reactor(MJ/s).

MW_e: Electric Power production in a nuclear reactor(MJ/s).

VHTR: Very High Temperature Reactor.