Dual Fluid

Reinventing Nuclear

Why reinvent nuclear power?

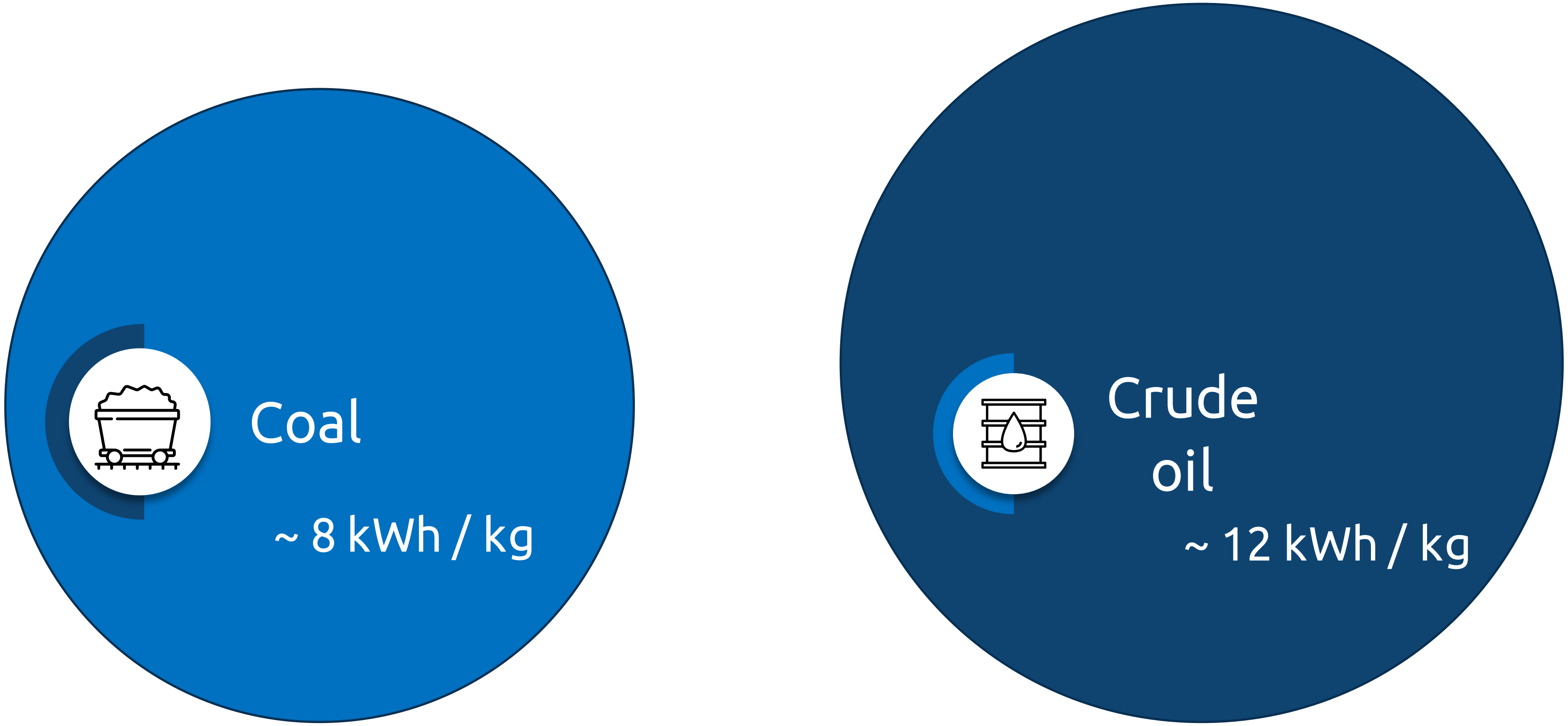
Energy defines civilization

Middle Ages	18th/19th century	21st century
• Discovery of concentrated fuels: coal, oil	• **Optimized use of coal + oil** through new technologies • 10 times more energy available than before	• **Optimized use of nuclear power**

Modern lifestyle
Double life expectancy

Dual Fluid

Energy content of fuels: Coal and crude oil



Dual Fluid

Energy content of fuels: Uranium

Coal	~ 8 kWh
Crude oil	~ 12 kWh
U Uranium	~ 24.000.000 kWh

Energy content of fuels: uranium

U **Uranium contains 2 million times more energy than fossil fuels!**

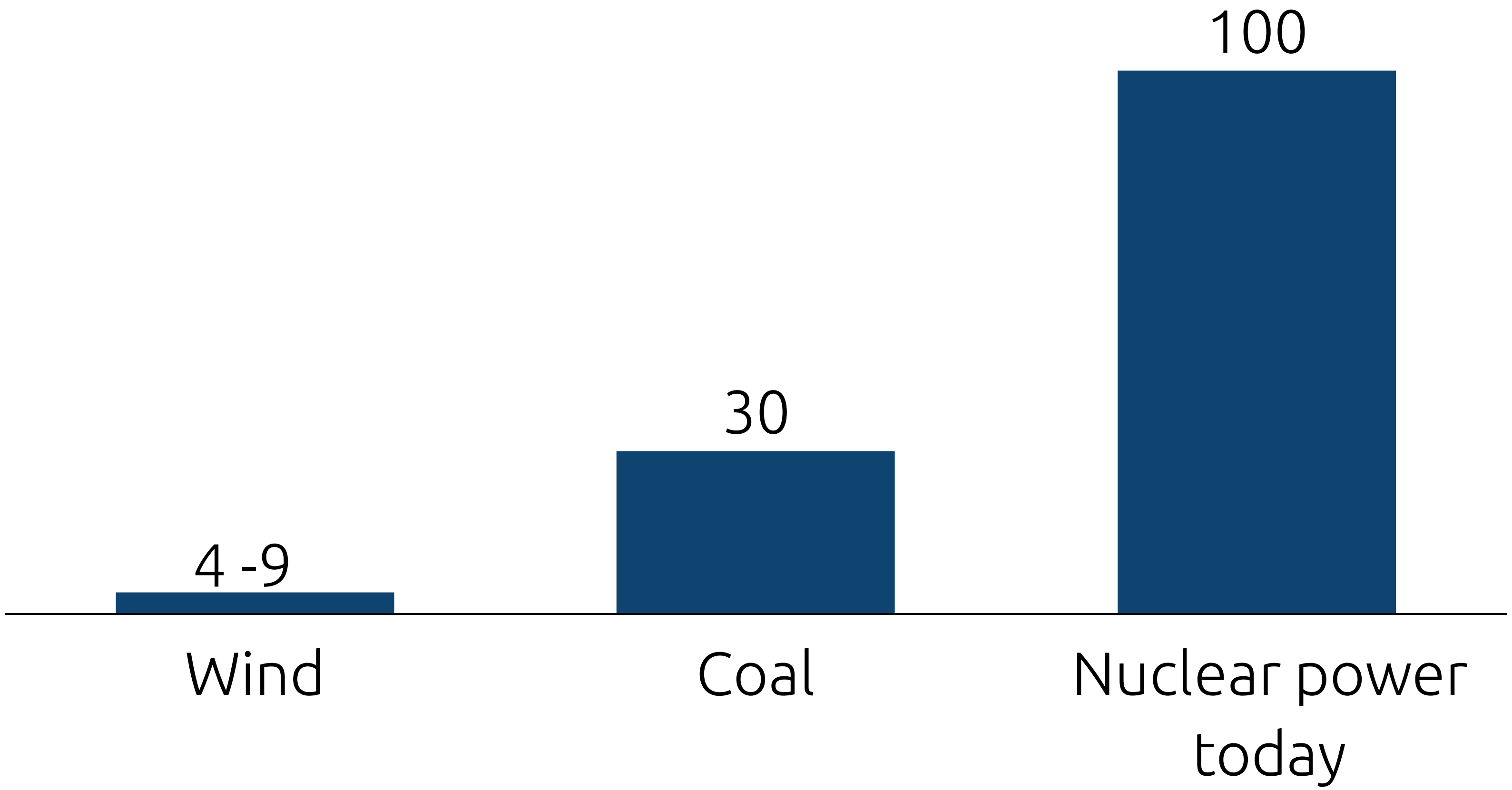
Power plant performance: Energy Return (EROI)

$$\text{EROI} = \frac{E_{out}}{E_{in}}$$

Energy Return on Investment (EROI) =.
Ratio of usable energy delivered (**E_{out}**) to the total amount of energy used for construction, fuel, maintenance, safety, dismantling, etc. of a power plant (**E_{in}**).

Power plant performance (EROI)

$$\text{EROI} = \frac{E_{out}}{E_{in}}$$



Dual Fluid

Status quo - potential - goal

Status quo: current nuclear power little stronger than fossils

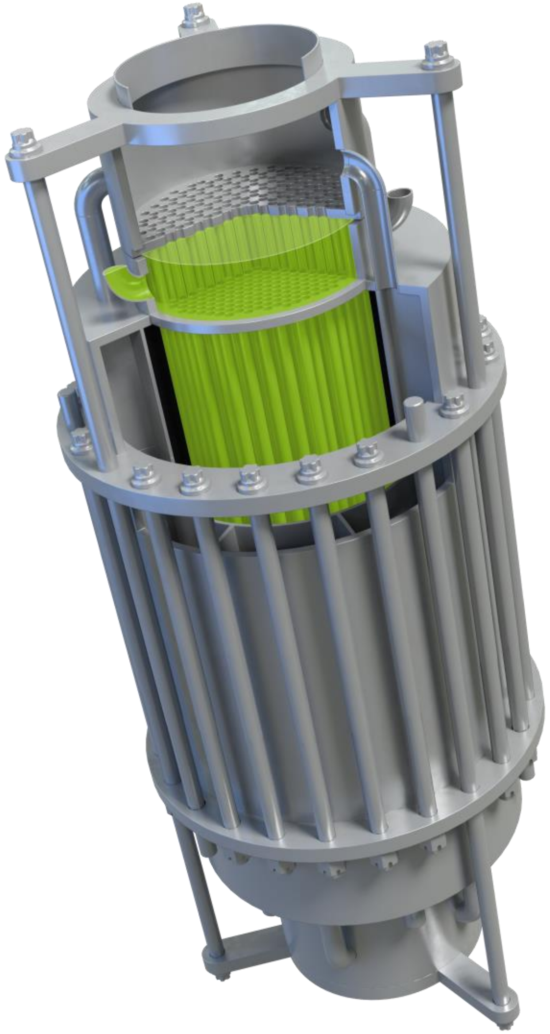
Potential: Uranium millions of times denser than fossils

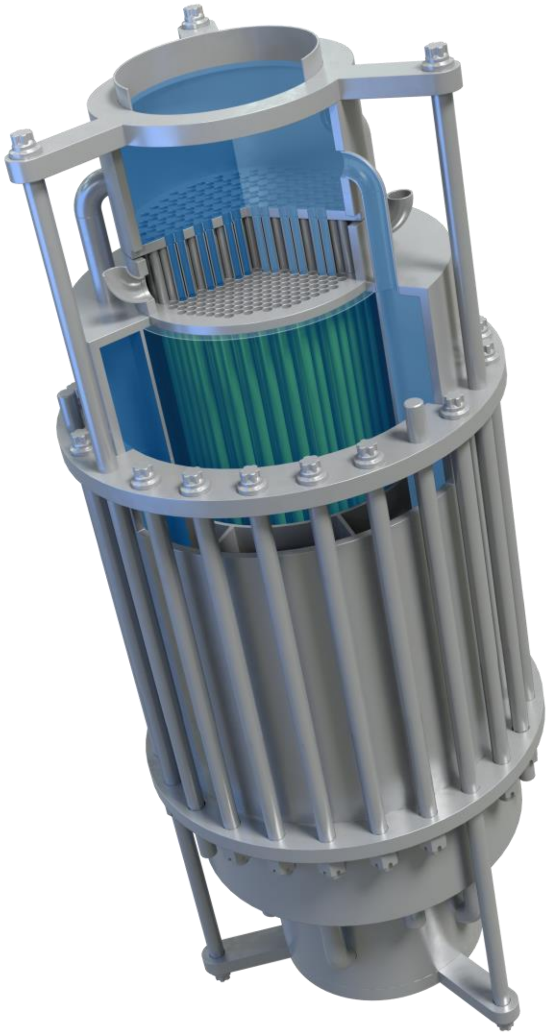
Goal: Fully exploit the power of the fuel

Our new design

The Dual Fluid principle

- **Liquid fuel:** thorium, natural uranium, processed nuclear waste > **optimum burnup**
- **Liquid coolant:** lead > **optimum heat removal**





Design advantages

1. Ideal fuel utilization
2. High temperature: 1000°C
3. Compact reactor core

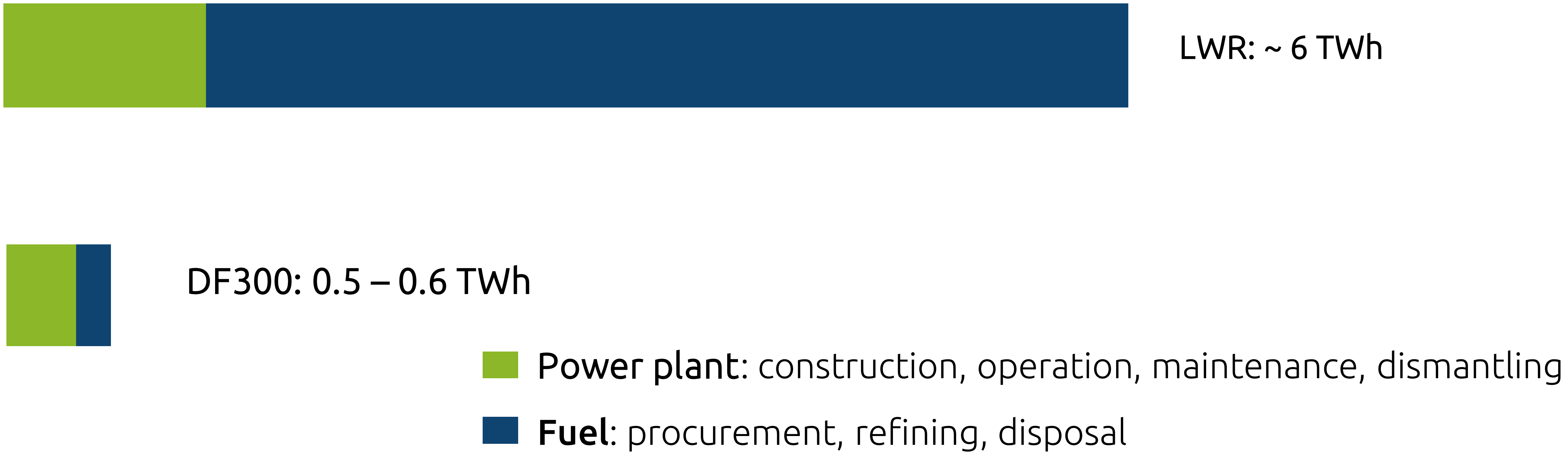
Maximum power density

Dual Fluid

Energy expenditure (E_{in}) LWR vs. Dual Fluid

Dual Fluid

E_{in} light water reactor vs. Dual Fluid

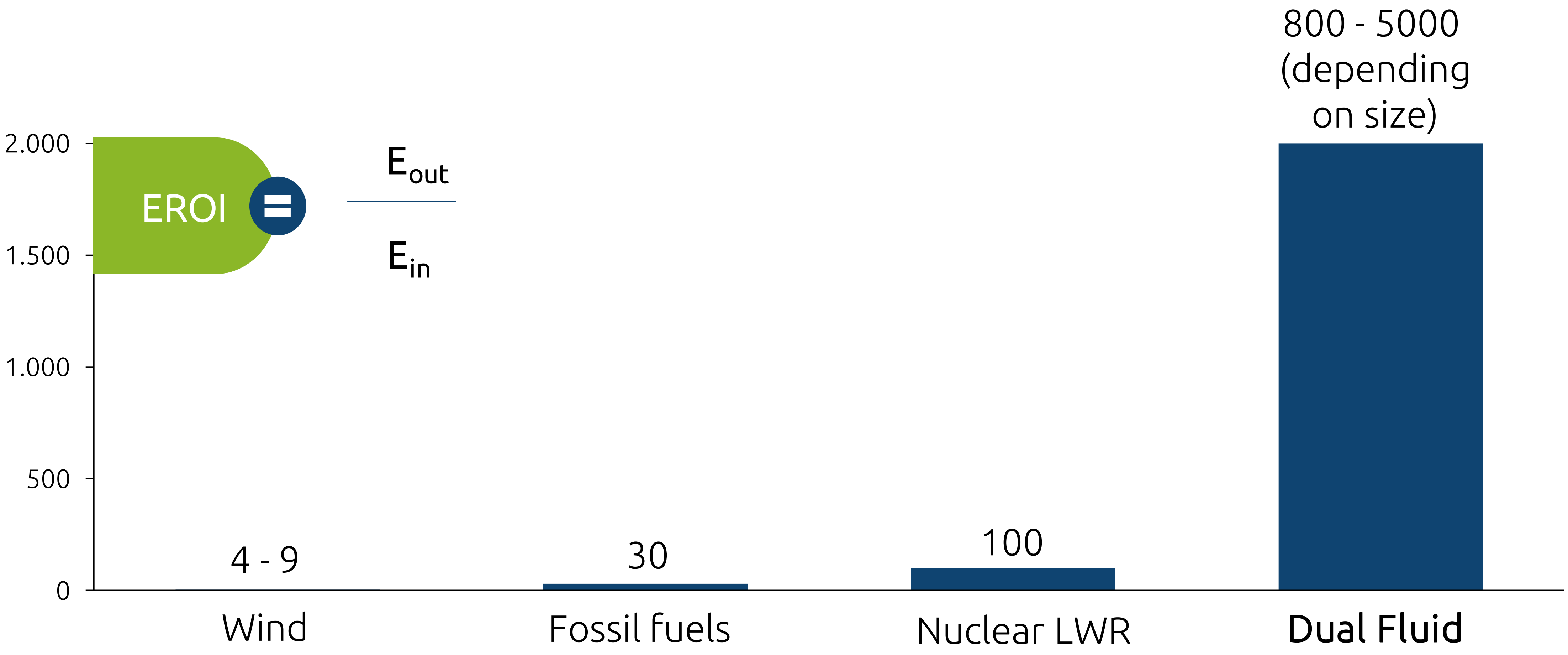


E_{in} light water reactor vs. Dual Fluid

Dual Fluid saves 90% of the energy expenditure

Dual Fluid

Energy Return Dual Fluid (EROI)



Energy costs

Cost comparison electricity

DF300 **halves today's electricity generation costs**

LCOE - LCOE[1] , US¢/kWh			
Gas	Nuclear power today	DF300	DF1500
7 – 9.5	6.5	2.7	2.1

1LCOE: Levelized Cost of Energy. Sources other than Dual Fluid: World Bank, 2020

Dual Fluid

Cost comparison hydrogen

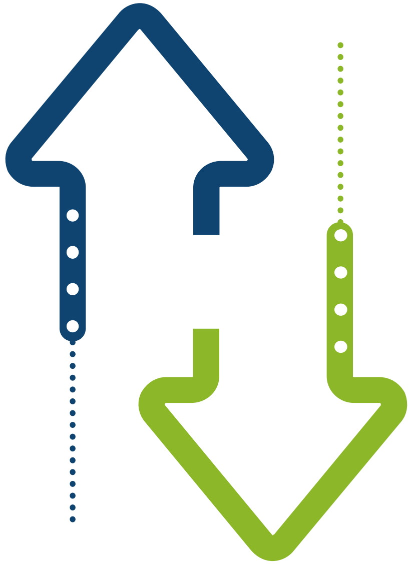
Dual Fluid produces **emission-free hydrogen at a fraction of the** price of hydrogen from wind energy (process: S-I cycle or HTE)

Total US¢/MJ [1]		
Wind energy	DF300	DF1500
6 - 8	**1.2 – 1.5**	**0.9 - 1**

1. calorific value: 125 MJ/kg

Opportunities

Share of efficiently produced energy in the overall energy mix increases



Energy costs decrease

Innovation

Sustainable growth

Prosperity

Dual Fluid

Safety

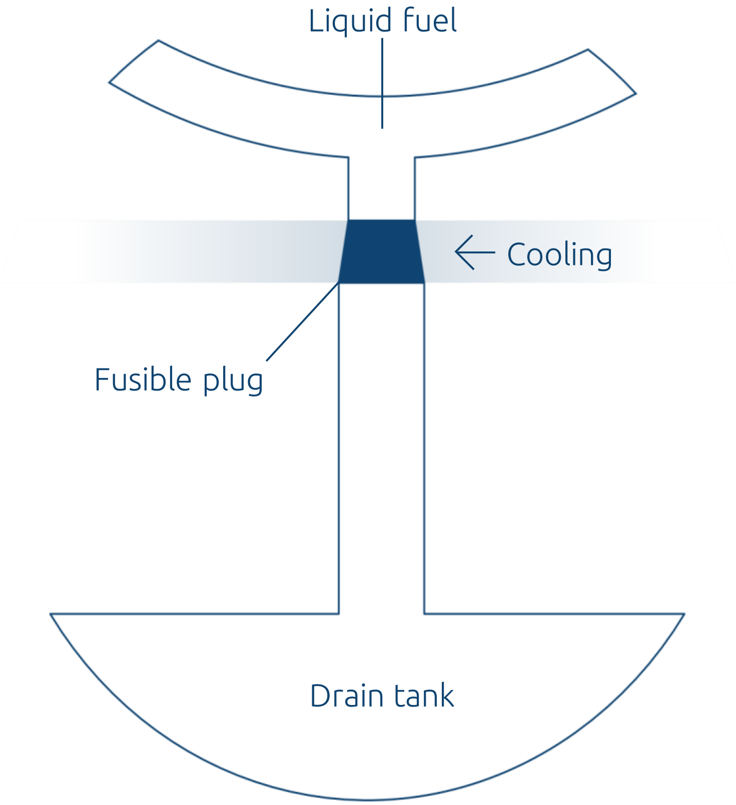
Triple protection

Self regulating temperature

→ "Core meltdown" ruled out

Underground containment

→ All substances safely stored



Fuse plug

→ Fuel drains into safe tanks when active cooling fails

→ **Walk-away-safe, even in case of incorrect operation**

Dual Fluid

Feasibility and timeline

Feasible with existing materials

Fuel and lead at 1000° C

Other industries: proven anti-corrosive materials available

Focus of established nuclear industry: low-cost materials (steel)

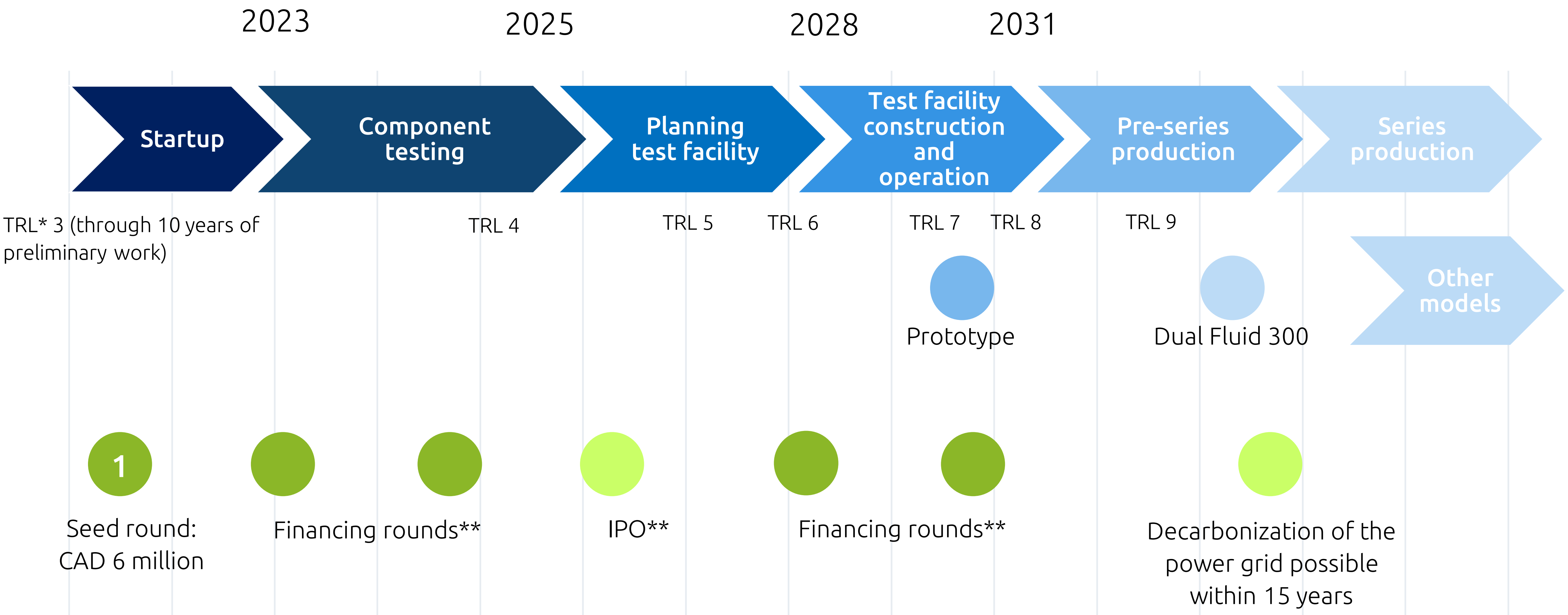
Reduced material costs with Dual Fluid: **expensive** materials possible

Possibilities: Refractory metal alloys and ceramics

1. Silicon carbide (SiC)
2. Zirconium carbide (ZrC)

Dual Fluid

Ready for series production within a decade



* Technology readiness level
** Prognostic development

Dual Fluid

Why Dual Fluid?

Dual Fluid...

makes full use of the fuel´s potential

cuts energy costs by half

can quickly be realized and applicated

Dual Fluid

Annex

Recycling with Dual Fluid

Step 1
Grinding and chlorination

- Decoring of the used fuel elements
- Pellets are finely ground and put into salt form

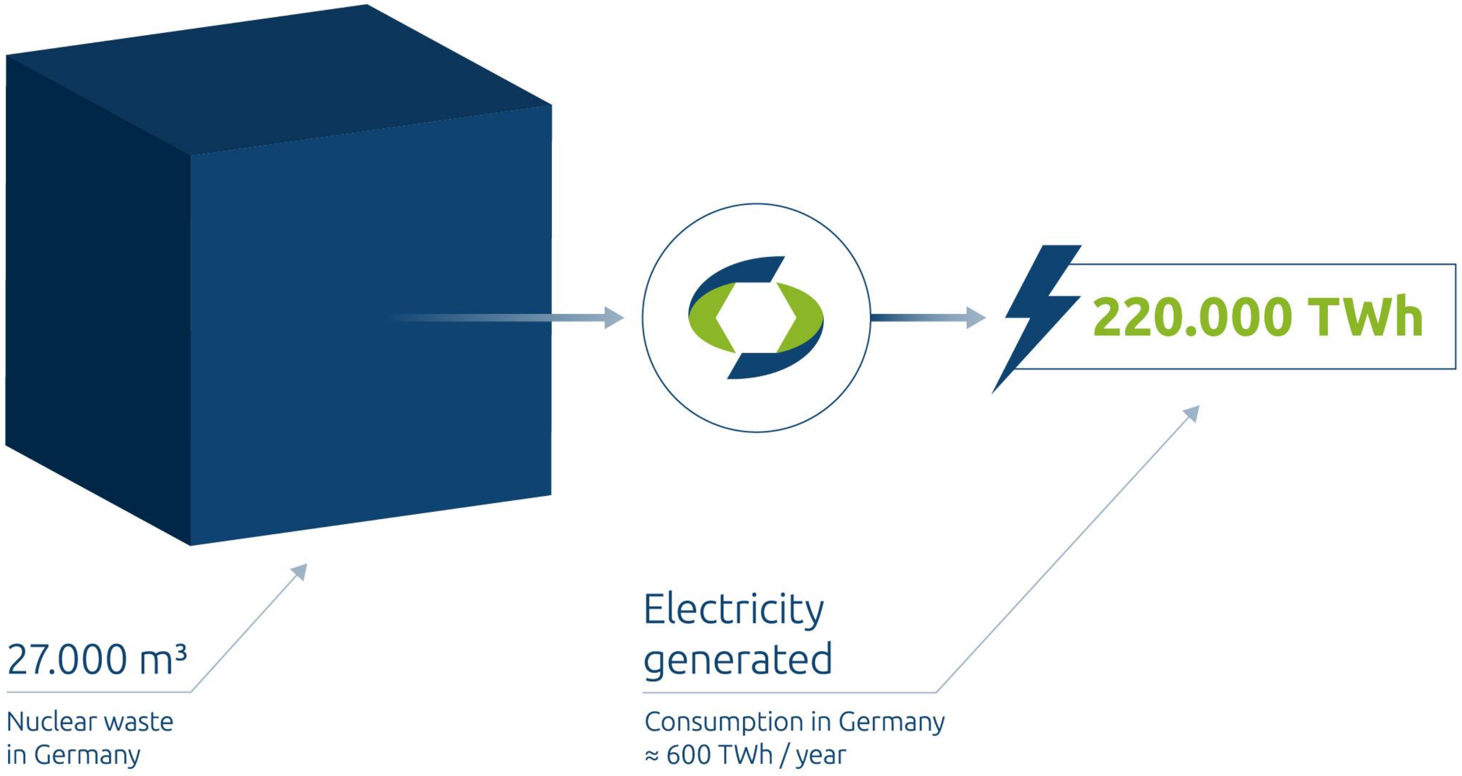
Step 2
Separate

- Separation of substances via pyrochemical distillation:
- Recoverable materials (uranium, non-weapons grade plutonium, etc.): 95%.
- Non-recyclable materials: 5% (storage period: a few hundred years)

Step 3
Recycle and transform

- Utilization in the reactor: electricity, process heat
- Transmutation of long-lived substances into short-lived ones

Tackling the waste



Nuclear waste is recyclable material

Energy utilization of long-lived nuclear waste or conversion to predominantly short-lived substances.

Shortened storage period

Radiation of residual materials (total amount) at the level of natural uranium within 300 years

Dual Fluid

Experienced, interdisciplinary team

Dr Armin Huke
President, Chairman of the Board of Directors

Doctorate in Nuclear Physics from TU Berlin. Since 2009 Managing Director of the Institute for Solid-State Nuclear Physics, Berlin. Main inventor.

Dr Götz Ruprecht
Managing Director, CEO

Doctorate in Nuclear Physics from TU Berlin. Research Associate at TRIUMF National Laboratory, Canada. Leadership of international research projects. Inventor.

Prof Ahmed Hussein
Director

Emeritus Professor of Physics at the University of Northern British Columbia. Leading research into Nuclear and Particle Physics at TRIUMF National Lab, Canada, and at Los Alamos National Lab, USA. Inventor.

Dr Titus Gebel
Director

Doctorate in law and MBA. Entrepreneur, incubator and investor. Founder and long-time CEO of Deutsche Rohstoff AG.

Dual Fluid

Experienced, interdisciplinary team

Dr Björn Peters
CFO

Physicist, owner of the research institute Peters Coll. for Policy Advising on Energy and Commodities. Many years of experience in power plant financing. Formerly McKinsey, Deutsche Bank AG and Deutsche Börse AG.

Dipl.-Ing. Stephan Gottlieb
COO

Senior technical officer at the Mechanical Engineering Laboratory, Dortmund University of Applied Sciences. Formerly Airbus Industries and Fraunhofer Institute. Inventor and developer, holder of numerous patents. Inventor.

Dipl.-Phys. Daniel Weißbach
CTO

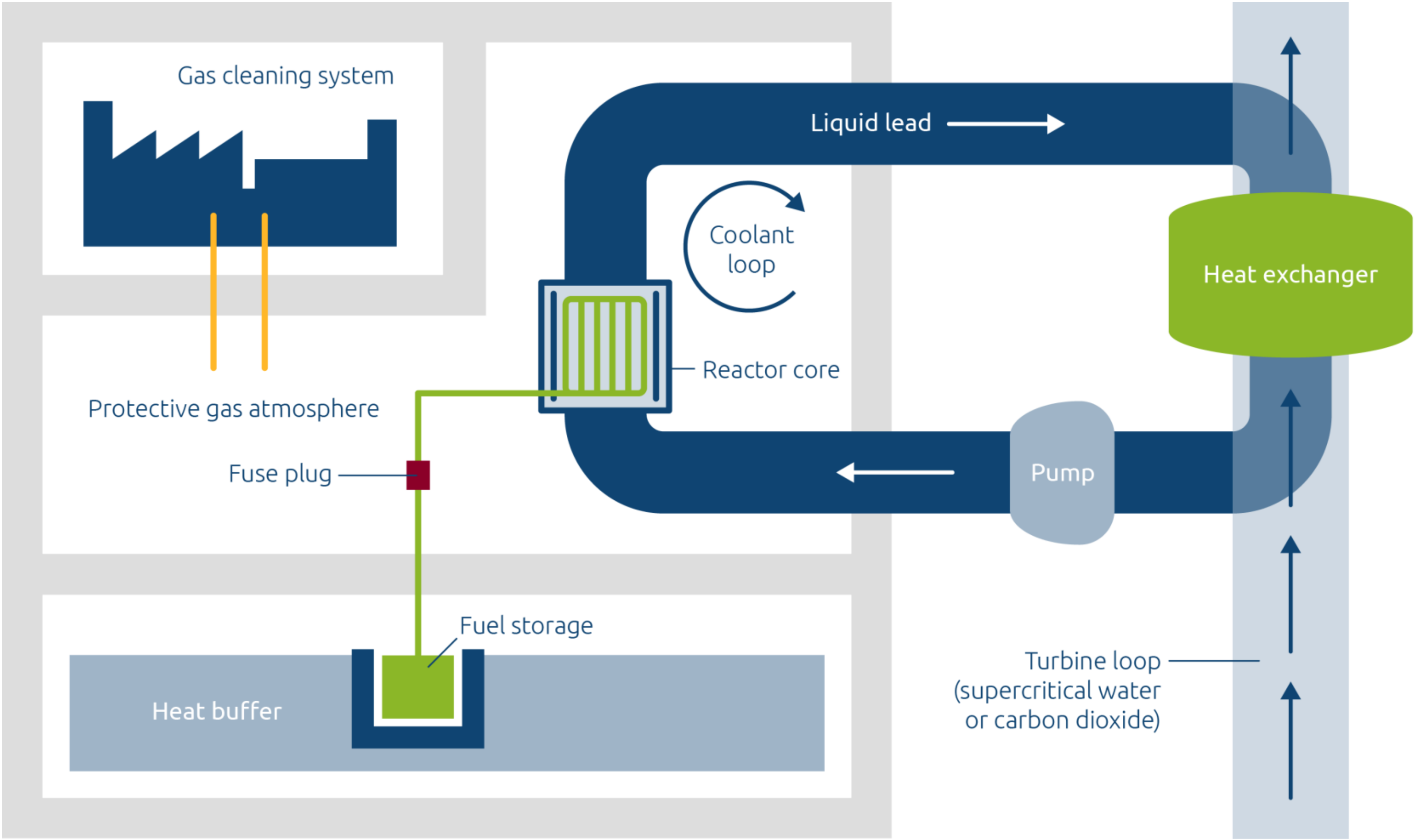
Graduate in Atomic Physics from TU Berlin. Research in nuclear physics and technology, studying for doctorate at Szczecin University and Institute for Solid-State Nuclear Physics Berlin. Inventor.

Lisa Raß
Head of Communications

Graduated in Literature and Linguistics. Worked in journalism and PR. Former nuclear power opponent, today supporting eco-modernity and nuclear humanism.

Dual Fluid

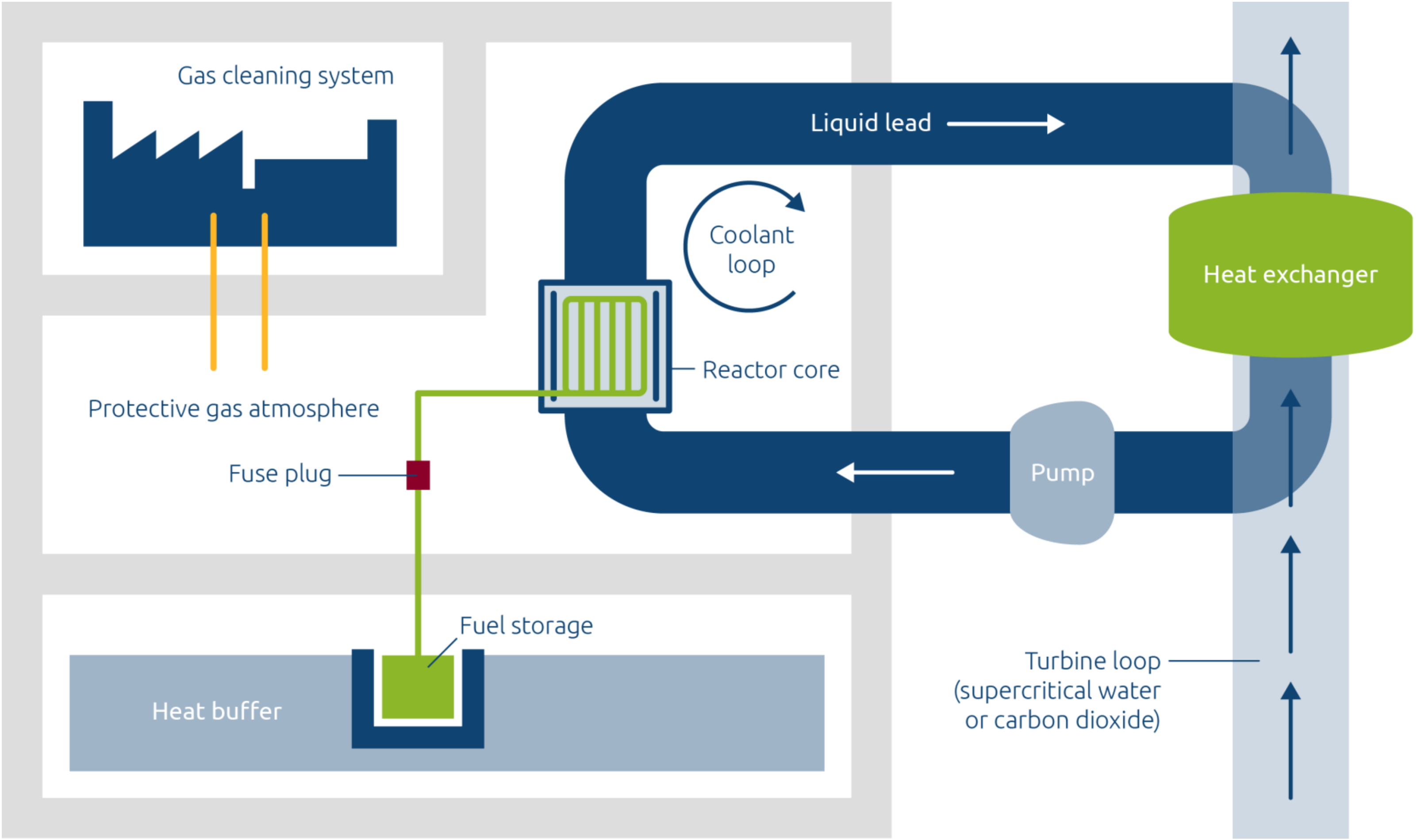
DF300 power plant (SMR)



- Fuel change intervals approx. 25 years
- Core and fuel cartridge exchangeable
- Burnup up to 200 MWd/kg $_{HM}$
- Utilization of nuclear waste in combination with external recycling plant
- Electricity generation with 50% efficiency, e.g. with supercritical media (scH_2O, $scCO_2$)

Dual Fluid

DF300 power plant: safety



- **Self-regulating,** homeostatic system
- Nuclear part of the plant **underground** for more safety
- Post-decay heat is passively removed > Overheating (**Fukushima**) impossible
- Core emptied > Chain reaction ends automatically > Uncontrolled chain reaction (**Chernobyl**) impossible

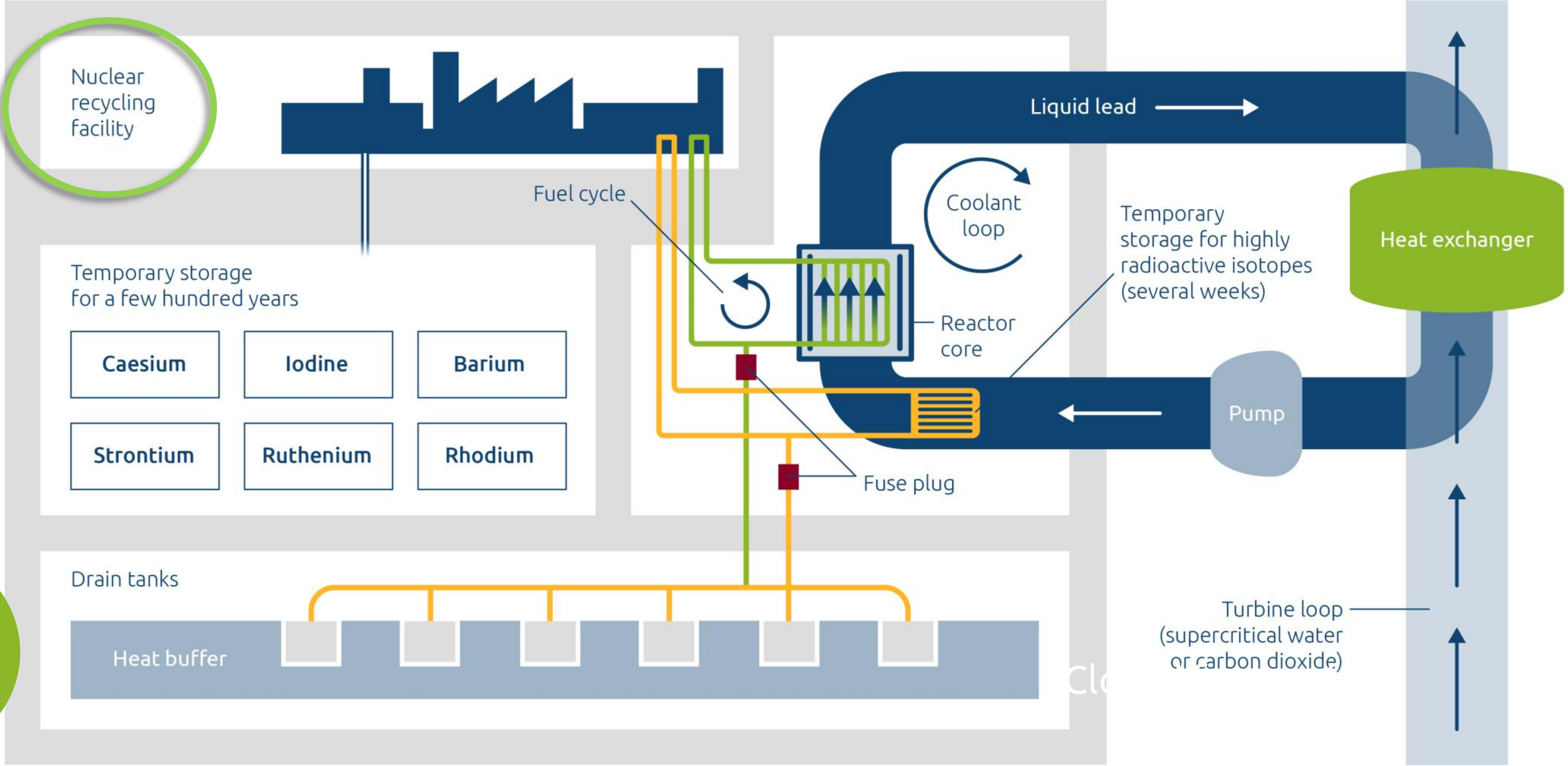
Dual Fluid

DF1500 power plant: Closes the fuel cycle

- Natural uranium
- Depleted uranium
- Thorium
- Used fuel elements

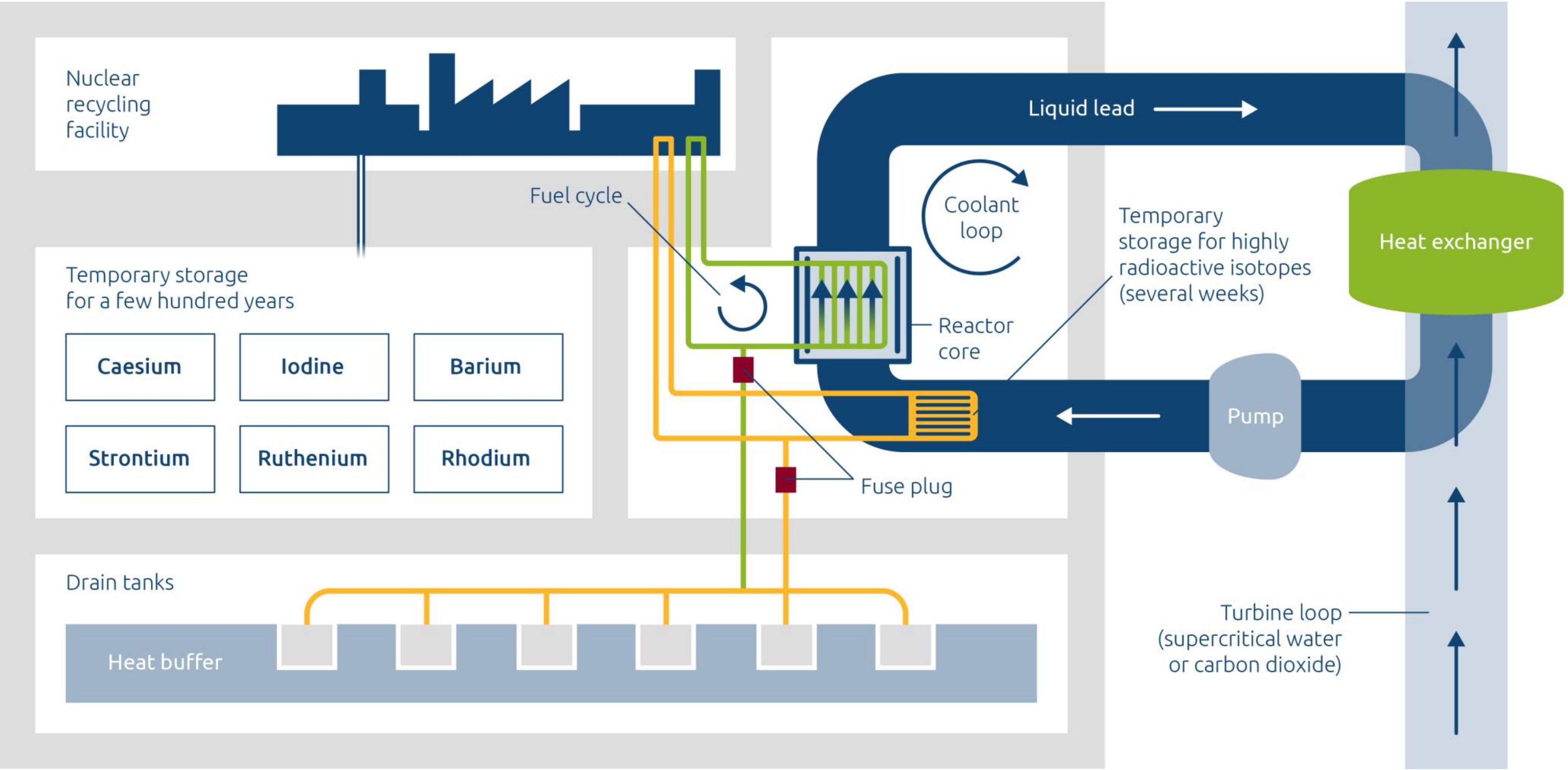
- Fission products
- Med. radioisotopes
- Fissile material

CLOSED FUEL CYCLE



Dual Fluid

Power plant DF1500



- On-site **storage of fission products** > ~300 years
- **Rare metals** purely available after a few hundred years
- **Power generation with efficiency > 50 %**, e.g. with supercritical media (scH_2O, $scCO_2$)
- High temperature process chemistry at 1000 °C

Dual Fluid

Is proliferation an issue?

The easiest and cheapest way to obtain weapons-grade plutonium **is not through a nuclear reactor.**

To extract weapons-grade material from a Dual Fluid power plant, **it would have to be completely rebuilt.**

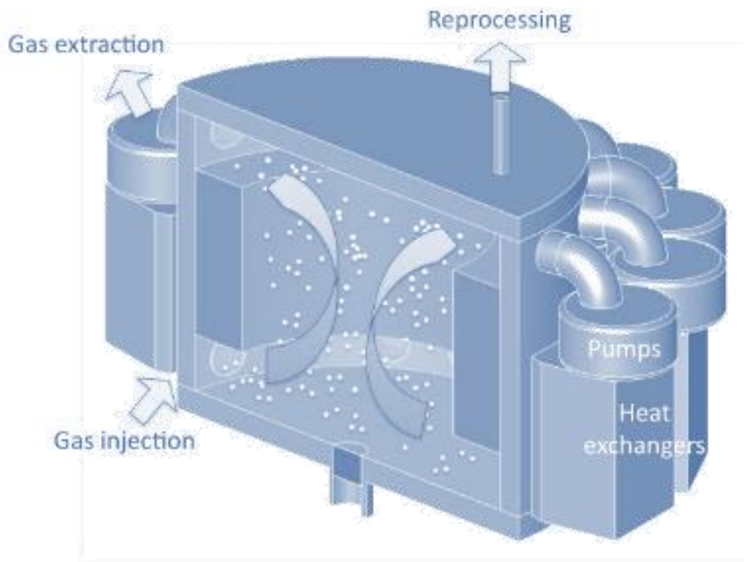
Since a Dual Fluid Reactor can also recycle plutonium from old nuclear weapons, it is **potentially a disarmament aid.**

Why is the Dual Fluid Reactor not an MSR?

Molten Salt Reactor (MSR) e.g. SAMOFAR

One liquid

- Homogeneous core
- Heat dissipation through the same fluid



Dual Fluid Reactor

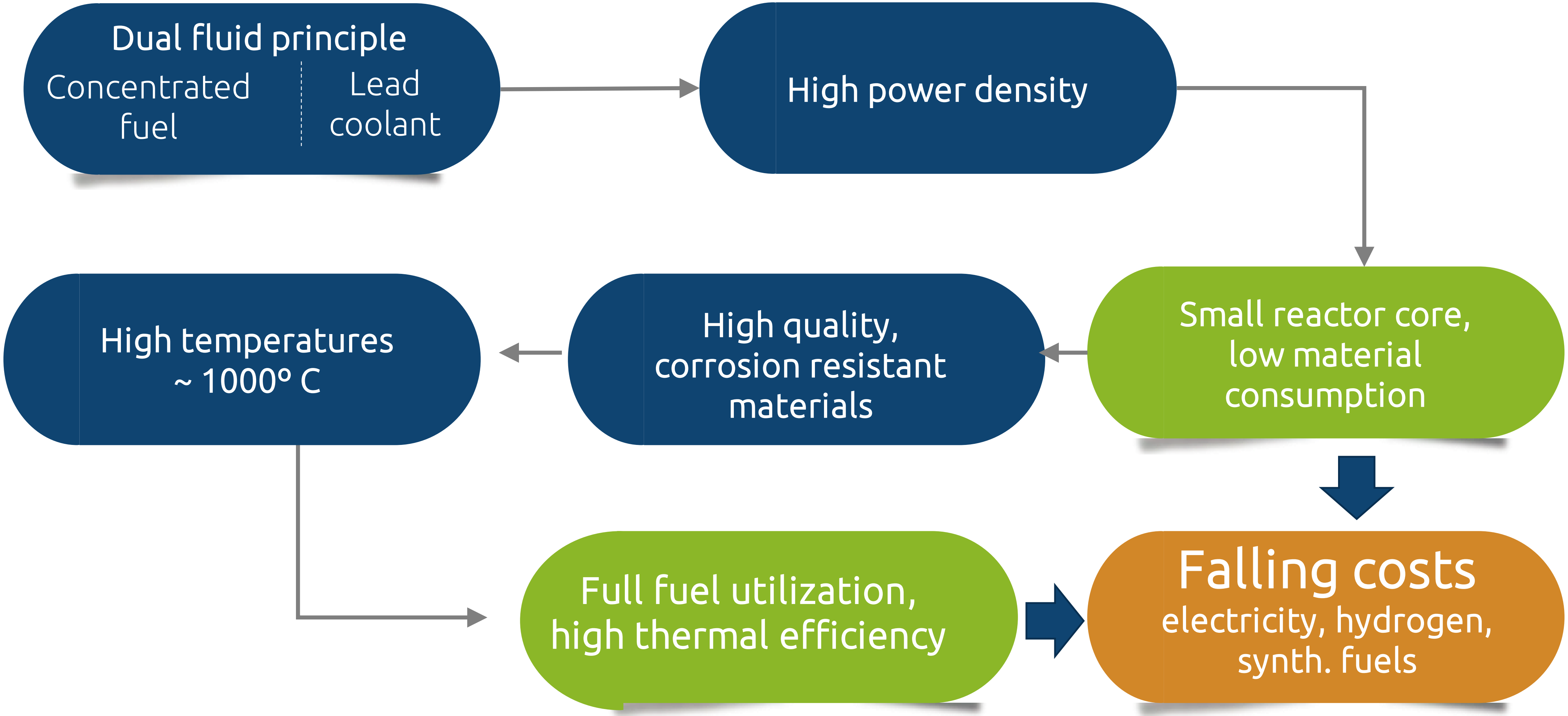
Two liquids

- Heterogeneous core
- Heat dissipation through second fluid

The dual function of fuel supply and heat removal in the MSR limits the power density.
Dual Fluid overcomes this limitation.

Dual Fluid

High power density, lower costs



Dual Fluid

Cost comparison fuel production

Method	Total US¢/MJ*			
	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)**	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 HTE	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	-	-	-

* Heating values of oil-based fuels, hydrazine, hydrogen, and ammonia: ~42 MJ/kg, 19 MJ/kg, 125 MJ/kg, and 18 MJ/kg
** Canadian oil sands supply costs and development projects (2016-2036), 2017, Canadian Energy Research Institute (CERI)
*** Current and future cost development depending on drilling height

Dual Fluid

Selected publications

Jakub Sierchuła et al, Int J Energy Res. 43 (2020) 3691: "Determination of the liquid eutectic metal fuel Dual Fluid Reactor (DFRm) design - steady state calculations."

Dominik Böhm et al, Acta Physica Polonica B 51 (2020) 893: "New methods for nuclear waste treatment of the dual fluid reactor concept."

Chunyu Liu et al, Metals 10 (2020) 1065: "Thermohydraulic analysis of the distribution zone in a small modular two-substance reactor."

Daniel Weißbach et al, Int. J. Energy Res. (2020)1: "Dual Fluid Reactor as a long-term burner of actinides in spent nuclear fuel".

Sang-in Bak et al, The European Physical Journal Plus 134 (2019) 603: "Design of an accelerator-driven subcritical dual fluid reactor for transmutation of actinides."

Xiang Wang et al, Int J Energy Res. 42 (2018) 4313-4334: "Steady-state reactor physics of the dual fluid reactor concept."

Thomas J. Dolan, "Molten Salt Reactors and Thorium Energy," Woodhead Publishing, 2017.

Xiang Wang, Dissertation 2017: "Analysis and Evaluation of the Dual Fluid Reactor Concept".

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 et al, Energy 52 (2013) 210: "Energy intensities, EROIs, and energy return times of power plants."

Armin Huke et al, Conference Paper from the 19th Pacific Basin Nuclear conference (PBNC 2014), Vancouver: The Dual Fluid Reactor - A New Concept For A Highly Effective Fast Reactor.

Jan-Christian Lewitz et al, atw 65 (2020) 145: The Dual Fluid Reactor - An Innovative Fast Nuclear Reactor Concept with High Efficiency and Total Burnup.