Nuclear Fusion: from Science Fiction to Science Fact

Tony Donné
CO$_2$!
Only 5.5% of all energy is really sustainable

Most from burning waste

Total World Energy Consumption by Source (2010)

- Fossil fuels 80.6%
- Renewables 16.7%
- Nuclear 2.7%

Bron: RENEWABLES 2012, GLOBAL STATUS REPORT

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World primary energy demand

Primary energy demand, 2035 (Mtoe)

Share of global growth 2012-2035

China is the main driver of increasing energy demand in the current decade, but India takes over in the 2020s as the principal source of growth.
Fossil fuel usage is still growing

Growth in total primary energy demand

- **Gas**: 1987-2011 (blue) / 2011-2035 (green)
- **Coal**: 1987-2011 (blue) / 2011-2035 (green)
- **Renewables**: 1987-2011 (blue) / 2011-2035 (green)
- **Oil**: 1987-2011 (blue) / 2011-2035 (green)
- **Nuclear**: 1987-2011 (blue) / 2011-2035 (green)

**Today's share of fossil fuels in the global mix, at 82%, is the same as it was 25 years ago; the strong rise of renewables only reduces this to around 75% in 2035**

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Clean energy?

Wind
Solar
Hydro
Waves / tidal
Biomass
Nuclear fission
Geothermal
CO$_2$-storage
deuterium + tritium \rightarrow \text{helium} + \text{neutron}
Nuclear Fission

\[ n + ^{235}\text{U} \rightarrow 3n + \text{fragmenten} \]
Fission

Fusion

$E = mc^2$
Europe, USA, Japan, China, Russia, S-Korea and India

want fusion:

• No CO\textsubscript{2} release, clean, safe
• Fuel abundantly available
• No proliferation issues

But... Fusion is impossible
Europe, USA, Japan, China, Russia, S-Korea and India

want fusion:

• No CO$_2$ release, clean, safe
• Fuel abundantly available
• No proliferation issues

But... Fusion is difficult
temperature: ~150 million°C

the D and T nuclei that need to fuse repel each other

brandstof: waterstof
10× hotter than the sun
Harnessing solar flares

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Thermal insulation: nearly perfect
Materials one can lay on the sun
Bombardment of neutrons
Fuel cycle
Tritium production
ITER: 34 countries
15.000.000 components
10× hotter than the sun
Making a plasma

Deuterium and Tritium

Heating

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Making a plasma

Plasma

Heating on
Harnessing solar flares
Confining a plasma

Hot plasma

Magnetic field

Heating high

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Confining a plasma

Hot plasma

Magnetic field

Heating high
Best confinement in a torus

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Plasma heating

Result: temperatures of 100 – 400 million K

Can be produced relatively simply

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JET and Medium-Size Tokamaks

JET AUG

MAST Upgrade TCV

JT-60SA

ITER

TCV

MAST Upgrade

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The winner: the tokamak
Concept improvement continues


Spherical Tokamak (MAST, UK)
Progress in fusion

ITER
Nett power gain:
\[ P_{\text{fusion}} = 10 \times P_{\text{in}} \]
Demonstration of technical principles

JET (and other machines)
Break-even:
\[ P_{\text{fusion}} = P_{\text{in}} \]
Emphasis on understanding the science

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Thermal insulation: nearly perfect
Ohmic heating: power coupled to confining magnetic field

- Total heating power
- Plasma radius


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Additional heating: decouple heating & confining B-field


Additional heating

Ohmic

stored energy

total heating power

12

temperature (keV)

Ω

plasma radius

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Gyro code; Jeff Candy

http://fusion.gat.com/omp/parallel/figures/supertorus-ib.jpg

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Hot plasmas have a rich structure

Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

Science 281, 1835 (1998)

Fluctuations lead to reduced performance

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1982 ASDEX: discovery of high confinement mode (F. Wagner)

- **Ohmic** heating
- **Additional heating**
- **Transport barrier**

- **Stored energy**
- **Total heating power**
- **Temperature (keV)**
- **Plasma radius**
Discovery of internal transport barriers

Ohmic

Additional heating

stored energy

total heating power

12

temperature (keV)

transport barrier

plasma radius

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Turbulence control

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Excitation and suppression of an island in TEXTOR

TEXTOR shot # 110212

- Red: Continuous ECCD/ECRH 200 [kW]
- Black: DED 2 [kA] AC+
- Blue: \( w \sim \sqrt{B_t/f} \)

Arbitrary Units

Time [s]

- 1 to 4

[V]

Time [s]

2.98 to 3.1

Line-of-sight ECE: \( f = 135.5 \) [GHz]

Line-of-sight ECE: \( f = 141.5 \) [GHz]

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The 7 challenges

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High T, magnetic confinement, turbulence control

Fusion: power multiplication factor doubles every 1.8 years

Moore’s law: number of transistors doubles every 2 years

Power multiplication

Multiplication power

High T, magnetic confinement, turbulence control

Fusion: power multiplication factor doubles every 1.8 years

Moore’s law: number of transistors doubles every 2 years

ITER

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Materials one can lay on the sun
Thermal power loads

Rolls Royce Trent 900

 ITER steady-state

 ITER transients

HWR

Re-entry vehicle

Ariane 5/Vulcain 2

Power load \([\text{MW/m}^2]\)

\(~1\)  \( <10\)  \( 85\)  \( 2000\)
Scrape-off layer ~ 2 cm thick

Power density 1 GW/m²
Proper choice of the divertor geometry

Radiate >90% of the power away (uniform distribution)

Decouple (detach) the plasma from the divertor (T<10 eV)
Heat Exhaust Research in Tokamaks

Research in alternative divertor solutions (Super-X, snowflake, liquid metal divertors)

Research in order to understand detached divertor conditions

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Studying Plasma Facing Components

Magnum-PSI

Pilot-PSI

PSI-2

JUDITH-1/2

WEST

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Erosion/redeposition

Reflectivity for eroded mirrors

Material eroded away elsewhere can be redeposited on mirrors
M. Rubel, 18th ITPA Diagnostics meeting

Courtesy: A. Litnovsky
High-power linear divertor simulators

Pilot-PSI

10 - 30 MW/m²

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Magnum-PSI

First super-conducting linear plasma simulator: steady state 3T

10 MW/m²
\( \Gamma_D = 10^{24} \text{ m}^{-2} \text{ s}^{-1} \)

Water cooled target (100 kW)
Water cooled wall (50 kW/m²)
Modular plasma source

Roots blowers:
60000 m³/h

Large targets (60 x 12 cm)
up to 100 kg

Turbo:
4400 l/s

Separate target analysis chamber

In-situ transfer from exposure to analysis chamber in 30 s
Detached plasma in Pilot-PSI
Bombardment of neutrons
High particle fluxes

50 × higher ion flux

5000 × higher ion fluence

> 10^5 × higher neutron fluence
Fuel cycle
Tritium production
Tritium must be used at least $1000 \times$ without being lossed

(each fusion reaction in the plasma must lead to creation of a new tritium atom in the blanket)
ITER: 34 countries
15,000,000 components
ITER Tokamak building
ITER 2011: building has started
ITER Headquarters opened in Oct. 2012
Building for winding poloidal field coils
Seismic insulation pads
483 Seismic insulation pads
Preparation for laying the ground floor
ITER vacuum vessel: more heavy than the Eiffel tower
Radial plates for the toroidal field coils
Winding the toroidal field coils

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Cooling system
Cryogenic system
ITER is a world wide project

Construction costs: ~15 billion Euro

First experiments: 2024

Power production: 500 MW

Power consumption: 50 MW
The future?

JET

ITER

DEMO

Fusion power

2000 2010 2020 2030 2040

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The 7 Challenges

ITER

IFMIF

Linear machines

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29 Research Units (+ numerous Third Parties) in 27 European countries working together to achieve the ultimate goal of the Fusion Roadmap
Eight important missions

- For each mission:
  - overview present status
  - list of unresolved and urgent issues
  - research & development plan
  - estimation of required resources

Three periods

- 2014 – 2020
  (Building ITER & Supporting Experiments)
- 2021 – 2030
  (Exploiting ITER and Designing DEMO)
- 2031 – 2050
  (Building and Exploiting DEMO)

Important to intensify the involvement of industry

https://www.euro-fusion.org/
Emphasis on:

- Central role of ITER
- DEMO as a single step to commercial fusion power plants that produce electricity and have a closed fuel cycle
- DEMO construction starting early in the 2030s
- Pragmatic Approach: It should not be perfect but good enough and must come on time to make an impact

**Fusion Roadmap**

- An ambitious yet realistic roadmap to fusion electricity by 2050
- Being implemented by a Consortium of Fusion Laboratories (EUROfusion)
- 8 Strategic Missions to tackle the critical challenges for Fusion:
  1. Plasma Operation
  2. Heat Exhaust
  3. Neutron resistant Materials
  4. Tritium-self sufficiency
  5. Safety
  6. Integrated DEMO Design
  7. Competitive Cost of Electricity
  8. Stellarator
A roadmap to the realisation of fusion energy

8 Strategic Missions tackle all challenges in two main areas:

**ITER Physics**
- Risk mitigation for ITER
- JET, Medium Size Tokamaks, Plasma Facing Component devices

**DEMO**
- Conceptual design studies
- A single step to commercial fusion power plants
- Production of electricity with a closed fuel cycle

**Back-up strategy**
- Stellarator
Missions 1 & 2

Mission 8

Also EFPW 2015
EUROfusion Programme management unit

THE EUROfusion PROGRAMME MANAGEMENT UNIT

PROGRAMME MANAGER

EUROfusion is all of us
Tony Donné

COMMUNICATIONS

Making communication flow
Petra Nielckan

“I am hoping to form one big team comprising the Programme Management Unit and the 29 Research Units.”

ADMINISTRATION

Meet the requirements of the new system
Christina Mrzez

“My goal is to deliver to the EUROfusion Programme Unit the operation of JET compatible with the roadmap.”

“My task is to ensure efficient administration and developing standards, procedures and guidelines that meet the need of all players.”

POWER PLANT PHYSICS AND TECHNOLOGY

Start putting the design and technology of Demo in the right context
Gianfranco Federici

“We have a very good team with excellent Project Leaders for the distributed PPPT Projects and a good PPPT PMI team with a balanced mix of senior experts and brilliant young engineers.”

ITER PHYSICS

ITER is the focus of our research
Xavier Litaudon

“ITER is the focus of our research, and the key to the success of the Fusion Community.”

“I dedicate my work to a long term goal: creating together with the Fusion Communicator’s Network a coherent European voice for fusion.”

ITER PHYSICS @JET

ITER PHYSICS @GARCHING

Xavier Litaudon

ITER
Darren McDonald

“EUROfusion has agreed a roadmap and common structure. This allows us to prepare for ITER exploitation and DEMO design as a unified team.”

“IN ORDER TO BEST PREPARE FOR ITER WE MUST HAVE ONE CONSISTENT PROGRAMME WITHIN WHICH TASK FORCES FOR ALL EUROPEAN FUSION EXPERIMENTS COLLABORATE CLOSER.”

JET EXPLOITATION UNIT

JET Operation
Lorne Norton

“My goal is to deliver to the EUROfusion Programme Unit the operation of JET compatible with the roadmap.”
The End
Questions:

Safety

When do we have fusion and how expensive?

Other forms of fusion

Economy – what determines the cost
Does fusion come in time?
Growth of various energy sources
(G.J. Kramer, Nature 2009)

ENERGY-TECHNOLOGY DEPLOYMENT

*Coal and natural gas used in power generation with carbon capture and storage

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Fusion compared to other sources

Preliminary version: numbers being checked! To be improved
Note also: Geuor/y scale applies to exponential growth phase only
Fusion is no chain reaction

Fuel for only a few seconds
Safety

Deuterium and helium are not radioactive

No transport of radioactive fuels during reactor operation

No long-living nuclear waste

No emittance of greenhouse gases
Nuclear waste

Nuclear fission

Nuclear fusion

Coal ash
Fuel makes up only 0.5% of the total costs!
Economy: Costs of the components

Important costs:

Blanket

Superconducting coils

buildings

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Economy: availability

Availability should grow in going from ITER via DEMO to the Fusion Power Plant

Projection of Electric Plant Availability

- Fission, Fossil
- Now
- DEMO
- ITER Operation
- FPP Operation?
Other forms of fusion
Inertial confinement fusion

Laser beams rapidly heat the inside surface of the hohlraum

X rays from the hohlraum create a rocket-like blowoff of capsule surface, compressing the inner-fuel portion of the capsule

Indirect-drive illumination

During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100 million kelvins

Fuel capsule compression

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy

Fusion ignition

Fusion burn

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Acoustic Magnetic Target Fusion

Magnetized Target Fusion

Compressed to thermonuclear conditions

Preheated fuel

Liner Implosion System

Plasma Injector

Plasma injector

Pneumatic pistons

Cylindrical vortex cavity

Plasma toroid

Rotating liquid lead/lithium solution within spherical tank

Plasma injector

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Muon-catalysed fusion
Confusion

Cold fusie

The Cold Fusion Reactor CFR v3.0 by Jean-Louis Naudin - May 2003

Fusor

Ball lightning

3 When top of wave reaches the bubble starts implosion. Vapours are quickly pressed and heated so fusion may occur.

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