Module 5 – Deployment

FuseNet educational materials for secondary school

Teacher's manual v.1.0

General introduction

Energy plays a fundamental role in our modern society. With the increasing growth of technologies and on the number of users of all these technologies, the world's energy demands are estimated to increase continuously. If we should continue the processes of generating energy than eventually the demand will be higher than we could possibly offer. Therefore, this series of lessons will provide insight to one of the relative new energy solutions: nuclear fusion.

Module 5 focusses on the role of fusion in the future energy market. It discusses the problems and possibilities.

This lesson series started with module 1 fusion basics, which will give the students the basics for all the other modules. **Therefore module 5 deployment can be used when the content of module 1 has been introduced.**

This series of lessons is intended for pre-university education: level ISCED 3-4.

Using the modules

The student readers consist of different lesson materials: the bright coloured boxes, which are called 'aside', will provide extra explanations of the underlying topics. These are optional to use in the classroom.

The light-coloured boxes provide classroom exercises. These can be used during class for further discussion and can serve as a check to test whether the students understand the material.

Next to the module there are also additional exercises. These exercises are scaled from * until ***, in which * corresponds to introductory problems and *** corresponds to more challenging problems.

The full content of a modules consists of:

- A student reader
    - including classroom exercises
- Additional exercises
- A PowerPoint
    - Including classroom exercises
- Teacher manual
    - Including the following appendices
        - Table of constants and conversion factors
        - Answers to the classroom exercises
        - Answers to the additional exercises

Content of the teacher manual

Chapter 1: Learning objectives

At the end of this module, students are able to:

- Explain today's electricity market
- Explain why fusion is not (yet) in today's electricity market
- Explain the problem of continuous energy production
- Understand the growth of energy demand
- Explain the advantages of a fusion power plant compared to conventional power plants
- Explain the disadvantages of a fusion power plant compared to conventional power plants
- Discuss the 'ideal' energy mix from an economical and societal view.
- Distinguish the differences of electricity and energy
- List multiple forms of energy

Chapter 2: Closely related subjects or lessons

Next to the subject of module 1 the following concepts are assumed to be known:

- Energy sources
    - Fossil
    - Wind
    - Sun
    - Nuclear fusion
    - Nuclear fission
- Chemical reaction
    - Endotherm
    - Exotherm
- Conservation law's and efficiency (and calculations of)
    - Energy
    - Power
    - Efficiency

These subjects are not required to be known by the students but can help to reach more depth within the different choices, inventions and problems

- Nuclear physics
    - Half-life
    - Beta decay

Chapter 3: Topics of Module 5 per chapter

The following topics are discussed per chapter in module 5

1. Fusion power
    - Energy
        - Energy sources
        - Consumption and production
    - Electricity
        - Electricity grid
        - Households vs industry
        - Plant availability
2. Changing demand and supply
    - Changes in energy demand

- Changes in electricity demand
  - Shift towards renewables
  - Baseload of electricity
  - Reworking of the grid

3. What can fusion add to the mix?
   - Baseload vs intermittent sources
   - Land use
   - Fuel depletion
   - Meltdowns weapons and waste
     - Nuclear waste
     - E-waste
   - Cost of Electricity
     - Levelized cost of electricity
4. What about the money?
   - Costs of a fusion power plant
     - Capital costs
       - Heating systems
       - Buildings
       - Magnet systems
       - Superconducting magnets
     - Cost of repairments
       - Remote handling
     - Cost of operation and maintenance
     - Cost of decommissioning
     - Cost of money
     - Investments
   - Costs of physical aspects
5. Can fusion become cheaper?
   - Maximising electricity production
     - Reactor availability
       - Repairments
       - Burn duty cycle
     - Plant efficiency
     - Net electric output
   - Technological learning
     - Progress ratio
     - Learning factor
6. ITER and onwards
   - ITER
   - IFMIF-DONES
   - DEMO
   - Breeding Tritium
     - Beta decay
     - Half-life
   - Chemical reactions
     - Endotherm
     - Exotherm
     - Atomic notation

Chapter 4: Brief summary of module 5

The goal of this chapter is to help put fusion in a broader perspective by looking at how fusion fits in the energy and electricity landscape of the future. A basic knowledge of nuclear fusion is expected as a result of module 1.

In the first chapter, students have a closer look at the difference between energy and electricity and the different sources of energy that are used today. How much would a fusion power plant produce and how does this compare to the energy needs of a household, a city, the world?

In the second chapter, the focus shifts from today to the future: as time goes on, there are changes in demand and supply and these are important for the possible use of a new energy source in the future such as fusion. Since the future is hard to predict we compare the current energy landscape to the expected landscape in 2040. There are two main roads to eliminating fossil fuels: replacing fossil fuels with another baseload electricity supplier or by reworking the grid.

The third chapter has a closer look at exactly what fusion would add to the future energy mix. It lists various advantages of nuclear fusion such as: possible baseload supplier, relatively little land use, enough fuel for the coming 1000 years, no meltdowns, no nuclear weapons and no long-lived radioactive waste. At the same time, there are also disadvantages: there still is nuclear waste and obtaining the fuel leads to its own set of problems to be discussed later in the module.

In the fourth chapter we have a look at the costs of a fusion power plant: where does all the money go and why are some parts so expensive? Most of the costs are capital costs, meaning that a fusion power plant is a very large initial investment. Constructing the heating systems, buildings and the magnet systems is the most expensive. The magnets are especially expensive, since this is new technology that has never been produced in this size. Repairments cannot be done by hand but need to be done remotely due to radioactivity and must not take too much time to keep the power plant viable. Running the power plant for its entire lifetime is only about 10% of the costs and the cost of money and investing should not be underestimated.

The fifth chapter investigates how fusion could become cheaper: assuming that the technological costs and costs of building remain similar, which knobs can be turned to maximise the plant's electricity production and lead to a drop in the cost of electricity? There are three: reactor availability, plant efficiency and the net electric output. Increasing these three will lead to cheaper fusion electricity. Also to be taken into account is the learning over time which occurs as fusion power plants are built. These can be quantified in the progress ratio and the learning factor.

In the final chapter we look at the future of fusion: ITER and onwards. ITER is currently being build and is a true experiment. To prepare for the devices after ITER a material irradiation facility is to be build in Europe: IFMIF-DONES. Here materials can be tested for future fusion devices. The goal is to then create a successor of ITER: DEMO. All major fusion players are planning their own DEMO and they are to be the first true fusion power plants, demonstrating production of electricity with nuclear fusion.

Chapter 5: Basic lesson schemes

There are three possible basic lesson schemes given. Each scheme will depend on the time available and the knowledge of the students. There is chosen to give a 15-minute lesson scheme and a 1-hour lesson scheme for an introductory lesson on fusion for both average and advanced students.

The starters scheme can be used if multiple or all topics are unfamiliar to the students. The advanced schemes can be used when most important topics for fusion are familiar to the students. Therefore, the advanced scheme will also have a shorter introduction and more time for discussion and exercises.

The advanced schemes serve as an example, feel free to choose the topics and/or chapters suitable for your class.

For all the lesson schemes the student activities involve listening, discussing, asking questions and working on exercises.

15-min introductory lesson for students

There are two goals for this lesson: to discuss the changing energy landscape and the role of energy sources therein and to look at how fusion might fit into this landscape in the future. The topic is well-suited for classroom discussions on climate change, fossil fuels, renewables and nuclear energy. This introductory lesson can be given to both average or advanced students. Depending on the students, the discussion can be taken to a different level.

In the introductory lesson, the focus is more on energy in general and possible advantages and disadvantages of fusion and the more technical or fusion specific topics are treated in less detail. Chapters 5.4, 5.5 and 5.6 can be skipped to keep the focus more broad.

An option is to have a class-wide discussion after going over the topics of chapters 1-3, or to make groups and let students discuss the topic and present their conclusions. After the introduction and/or discussion, the students can read the student reader, work on exercises or work on topics of their choice.

Preparation for this lesson involves:

- Downloading the PowerPoint
- Making the module and exercises available for students
- Preparing classroom exercise 5.1 and 5.3

Duration	Teacher activity	Materials	Student activity
3 min	Chapter 1: Energy and electricity	Chapter 1: PowerPoint slide: 3 → 12	Listen, ask questions
2 min	Classroom exercise 5.1	Powerpoint slide 10	Work on the problem
2 min	Presenting chapter 2: Changing demand and supply	Chapter 2: PowerPoint slide 15-16, 19-20 (skip exercise 5.2)	Listen, ask questions
3 min	Chapter 3: What can fusion add to the mix?	Chapter 3: PowerPoint slide 21-22, 25-26	Listen, ask questions
5 min	Discussion on the energy landscape of the future. How does fusion fit in?	Chapters 1-3 PowerPoint slides 3-26	Classroom discussion: do students think fusion will have a place in the energy landscape of the future? Why (not)?

1-hour lesson for average students

The one-hour lesson starts similar to the 15-minute lesson: first the changing energy landscape is discussed and the role fusion could have therein. The rest of the lesson is dedicated to a practical look at fusion as an energy source. The focus is not on the physics, but a more economical perspective is taken, with an in depth look at very practical and important concepts for power plants and energy generation such as the costs, construction issues and power plant operation and management.

The material needed covers the whole of module 5. From the additional exercises * and possibly ** could be used. The asides material is reading material for the students. The whole PowerPoint can be used.

Preparation for this lesson involves

- Download the PowerPoint
- Make the module and exercises available for students
- Prepare classroom exercises if necessary

Depending on the students it is an option to give one full lecture of all the topics or to divide the lesson into four different parts. Each part includes an introduction of one of the chapters, time for classroom discussion and room to exercise.

Duration	Teacher activity	Materials	Student activity
5 min	Chapter 1: Energy and electricity	Chapter 1: PowerPoint slide: 3 → 12	Listen, ask questions
5 min	Classroom exercises 5.1 and 5.2	PowerPoint slide 10 and 13	Work on the problems
2 min	Presenting chapter 2: Changing demand and supply	Chapter 2: PowerPoint slide 15-16	Listen, ask questions
3 min	Classroom exercise 5.3	PowerPoint slide 17	Work on the problem
3 min	Continue with Chapter 2	PowerPoint slides 19-20	Listen, ask questions
3 min	Chapter 3: What can fusion add to the mix?	Chapter 3: PowerPoint slides 21-22	Listen, ask questions
3 min	Classroom exercise 5.4	PowerPoint slide 23	Discuss the problem
3 min	Continue with Chapter 3	PowerPoint slides 25-26	Listen, ask questions
5 min	Chapter 4: What about the money?	PowerPoint slides 27-31	Listen, ask questions
5 min	Classroom exercise 5.5	PowerPoint slide 32	Look up numbers, discuss with classmates
5 min	Continue with Chapter 4	PowerPoint slides 34-35	Listen, ask questions

3 min	Chapter 5: Can fusion become cheaper?	PowerPoint slides 36-37 and 41-43 (skip classroom exercise 5.6)	Listen, ask questions
5 min	Chapter 6: ITER and onwards	PowerPoint slides 44-45 and 48	Listen, ask questions
10 min	Discussion on the energy landscape of the future. How does fusion fit in?	Entire module	Classroom discussion: do students think fusion will have a place in the energy landscape of the future? Why (not)?

1-hour lesson for advanced students

The one-hour lesson starts similar to the 15-minute lesson: first the changing energy landscape is discussed and the role fusion could have therein. The rest of the lesson is dedicated to a practical look at fusion as an energy source. The focus is not on the physics, but a more economical perspective is taken, with an in depth look at very practical and important concepts for power plants and energy generation such as the costs, construction issues and power plant operation and management.

The material needed covers the whole of module 5. From the additional exercises * and possibly ** could be used. The asides material is reading material for the students. The whole PowerPoint can be used.

Preparation for this lesson involves

- Download the PowerPoint
- Make the module and exercises available for students
- Prepare classroom exercises if necessary

Depending on the students it is an option to give one full lecture of all the topics or to divide the lesson into four different parts. Each part includes an introduction of one of the chapters, time for classroom discussion and room to exercise. For advanced students, classroom exercise 5.6 can be given as an exercise during the lesson or given as homework after the lesson. If the concept of half-life/radioactive decay is known to students, it is also very interesting to combine this knowledge with the ASIDE on tritium breeding.

Duration	Teacher activity	Materials	Student activity
5 min	Chapter 1: Energy and electricity	Chapter 1: PowerPoint slide: 3 → 12	Listen, ask questions
5 min	Classroom exercises 5.1 and 5.2	PowerPoint slide 10 and 13	Work on the problems
2 min	Presenting chapter 2: Changing demand and supply	Chapter 2: PowerPoint slide 15-16	Listen, ask questions
2 min	Classroom exercise 5.3	PowerPoint slide 17	Work on the problem
3 min	Continue with Chapter 2	PowerPoint slides 19-20	Listen, ask questions
3 min20	Chapter 3: What can fusion add to the mix?	Chapter 3: PowerPoint slides 21-22	Listen, ask questions
3 min	Classroom exercise 5.4	PowerPoint slide 23	Discuss the problem
2 min	Continue with Chapter 3	PowerPoint slides 25-26	Listen, ask questions
5 min30	Chapter 4: What about the money?	PowerPoint slides 27-31	Listen, ask questions
5 min	Classroom exercise 5.5	PowerPoint slide 32	Look up numbers, discuss with classmates

2 min	Continue with Chapter 4	PowerPoint slides 34-35	Listen, ask questions
3 min	Chapter 5: Can fusion become cheaper?	PowerPoint slides 36-37	Listen, ask questions
5 min	Classroom exercise 5.6	PowerPoint slides 38-39	Work on the problem
5 min	Continue with Chapter 5	PowerPoint slides 41-43	Listen, ask questions
5 min	Chapter 6: ITER and onwards	PowerPoint slides 44-45 and 48	Listen, ask questions
5 min	Discussion on the energy landscape of the future. How does fusion fit in?	Entire module	Classroom discussion: do students think fusion will have a place in the energy landscape of the future? Why (not)?

Chapter 6: Use of PowerPoint and other materials

There is a PowerPoint (for each module) available at the site: https://fusenet.eu/education/material.

The PowerPoint consists of the whole module, including the classroom exercises and answers, and can be used directly in class. There are some extra pictures used to explain the topics. For an overview of extra material see chapter 7. You can adapt the PowerPoint to the topics which are treated in the classroom.

To introduce the different topics of module 5, it is possible to give the students a preparation exercise at home per topic. This could be one or more of the classroom exercises. For the preparation also some subjects from 'further references for study and fun' can be used.

Chapter 7: Further references for study and fun for module 5:

For teachers

The following contains general background information (in English) for teachers of this module. This is merely intended to use for your own knowledge and understanding of the subject. It is possible to use this content in the classroom but then it has to be adapted to the level of the students.
Some sites will give information about the topics covered or related to this module. Other sites also give pictures. Under each URL there is a short introduction of what can be found.

a. FuseNet website - https://www.fusenet.eu/education/material
Here you can find the other four modules. Furthermore, there are also theoretical papers, courses and experiments of topics related to this lesson series.

b. EUROFusion - https://www.euro-fusion.org/ There is a special page for students and educators. Educators will find more information on the basics of the topics and there is a Q&A for fusion. There are also slides and PowerPoint presentations available which are free to use. Students can find the same type of content on the website but the information is more to the point and appropriate for students. It can be used for both average and advanced students.

c. Fusion for energy - https://fusionforenergy.europa.eu/
This website has nice animations regarding fusion and the basics of fusion. It uses clear explanation regarding the different topics of module 1 and also ITER. However due to the animation the website can be slow.

For teachers and students

If you want to learn more about the future of fusion in Europe and want to know the current timelines, then the EUROfusion fusion roadmap is the most important document. There exist different versions, short summaries and extensive reports that give a quick overview of fusion research goals and timelines or an extensive overview of all research activities. Have a look at:
https://www.euro-fusion.org/eurofusion/roadmap/

Additionally, the ITER milestones give an interesting overview of the near-future:
https://www.iter.org/proj/itermilestones

Appendix A: Table of constants and conversion factors

Quantity	**Quantity**	**Conversion factor to SI units**
Energy[1]	1 Calorie	4.184 J
Energy[3]	1 toe*	$4.2 * 10^{10}$ J
Energy[1]	1 kWh*	$3.6 * 10^{6}$ J
Mass[1]	1 Ton	$1.0 * 10^{3}$ kg
Mass [1]	1 amu/u/ame	$1.66 * 10^{-27}$ kg
Temperature[1]	0 °C	273.15 K
Pressure[1]	1 bar	$1.0 * 10^{5}$ Pa

Table A.1 conversion factors

*students are asked to find these in exercises A.2

Quantity	
Core temperature Sun[2]	$1.571*10^{7}$ K
Surface temperature Sun[1]	5780 K
(mean)Density Sun[2]	1408 kg/m^3
Core density[2]	$1.622*10^{5}$ kg/m^3
Core pressure Sun[2]	$2.477*10^{11}$ bar
Surface temperature Earth[1]	295 K
(mean) Density Earth[2]	5514 kg/m^3
Mass electron[1]	$9.109 *10^{-31}$ kg
Charge electron[1]	$1.602*10^{-19}$ C
Mass proton[1]	$1.673*10^{-27}$ kg
Charge proton[1]	$1.602*10^{-19}$ C
Mass neutron[1]	$1.675*10^{-27}$ kg

Table A.2 constants

[1] Noordhoff uitgevers & NVON (2021). *Binas HAVO/VWO Informatieboek 6de editie (6e havo/vwo)* (01 ed.). Groningen, Nederland: Noordhoff Uitgevers.

[2] Sun Fact Sheet. (2018). Retrieved 13 July 2021, from https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

[3] IEA Unit converter and glossary, for common energy units. From https://www.iea.org/reports/unit-converter-and-glossary

Appendix B: Solutions to classroom exercises

Classroom exercise 5.1

(a) Calculate this conversion rate yourself.

1 kWh = 1000 W × 1 h = 1000 W × 60 min × 60 s = 1000 × 3600 (W × s)
1 kWh = 3 600 000 J, since Watt = Joule/seconds → (Watt × seconds) = Joules

(b) Using the table, calculate a household's yearly electricity consumption in J.

3700 kWh/yr = 3700 kWh/yr × 3 600 000 J/kWh = 1.332 × 1010 J/yr ≈ 13.32 GJ/yr

(c) Calculate how many households can be powered in a year by a 1-GW nuclear power plant.

1 GW × 1 yr = 1 000 000 kW × 365 days/yr × 24 h/day ≈ 8.76 × 10^9 kWh

→ a 1 GW power plant produces 8.76 × 10^9 kWh (or 3.15 × 10^{16} J = 31.5 PJ) of energy in a year. One household requires 3700 kWh per year, so one 1 GW power plant can power:

8.76 × 10^9 kWh / 3700 kWh/household = 2.37 × 10^6 households

So about 2.37 million households in a year

Classroom exercise 5.2

(a) Calculate the amount of electricity produced in a year.

1 GW × 8760 h × availability × capacity factor = energy per year
1 GW × 8760 h × 0.95 × 0.6 ≈ 4993 GWh of energy per year

(b) Calculate how many households can be provided for with a single plant.

4993 GWh / 3700 kWh/household ≈ 1.35 million households per year

(c) Calculate how many plants we would need to provide for the electricity demand of the entire world.

22 000 000 000 000 kWh/yr / 4 993 000 000 kWh/yr ≈ 4400 fusion power plants to supply the whole world in electricity (NOT energy!)

Classroom exercise 5.3

(a) Convert the electricity consumption and total energy consumption in both 2018 and 2040 to kWh.

2018: ~8.2 Gtoe from figure; 8.2 Gtoe = 8.2 × 10^9 toe = 8.2 × 10^9 × 11.63 MWh
→ 8.2 Gtoe ≈ 8.2 × 11.63 × 10^9 × 103 kWh ≈ 9.5 × 10^{12} kWh

2040: ~10.2 Gtoe from figure; 10.2 Gtoe = 10.2 × 10^9 toe = 10.2 × 10^9 × 11.63 MWh
→ 10.2 Gtoe ≈ 10.2 × 11.63 × 10^9 × 103 kWh ≈ 12 × 10^{12} kWh

(b) Convert the electricity consumption and total energy consumption in both 2018 and 2040 to J.

Converting from kWh to J: 1 kWh = 3 600 000 Joule
2018: 9.5 × 1012 kWh × 3 600 000 Joule/kWh ≈ 3.4 × 1020 Joule
2040: 12 × 1012 kWh × 3 600 000 Joule/kWh ≈ 4.3 × 1020 Joule

(4.3 × 1020 - 3.4 × 1020)/ 3.4 × 1020 × 100% ≈ 26.5%, so an increase of 26.5%!

Classroom exercise 5.4

A tokamak requires many auxiliary installations, of which some of the most important are the cryoplant (for cooling), diagnostics buildings, buildings for the heating systems (either NBI buildings or radiofrequency generator buildings), power conversion buildings to convert the currents that go into the magnets, a switchyard to get electricity from/to the grid, etc. See also figure 5.10, which shows all the different buildings required for the ITER tokamak. Note also all the different buildings just needed for the construction of ITER: because the magnets need to be build on site, there is also a magnet winding facility and cleaning facilities to make sure all the parts are thoroughly clean before they can be assembled.

Classroom exercise 5.5

(a) What are the critical temperatures of NbTi and Nb_3Sn in degrees Celsius?

NbTi: 9.2 Kelvin = -264 degrees Celsius
Nb_3Sn: 18 Kelvin = -255 degrees Celsius

(b) How do these critical temperatures compare to the boiling points of liquid nitrogen (–196 °C) and liquid helium (-268.95 °C)? Which of the two do you expect to be cheaper as a coolant? And which do we need to cool NbTi and Nb_3Sn?

Liquid nitrogen is not cool enough to cool below the critical temperature of either. Liquid helium is sufficient for both! So we need to use liquid helium to cool the superconductors. Nitrogen is the most common element in regular air (78%), so it is widely available and easy to get. Helium can be made from natural gas of the right chemical compositions or found naturally as a product of radioactive decay under the Earth's crust. Hence, helium is much more difficult to find and thus more expensive.

(c) Why is the critical temperature of REBCO an advantage?

Because the critical temperature of the REBCO superconductor is higher, there is more room for error: when the cooling system fails very briefly, the temperature in the superconductor rises quickly. If it rises above the critical temperature, suddenly the conductor is no longer super: there suddenly is a resistance, which leads to heat dissipation. The magnet then fails completely, and induction induces very extreme fields that shake the machine violently.

When the difference between cooling temperature and critical temperature is big, this can more easily be avoided.

Classroom exercise 5.6

(a) What is the maximum burn duty cycle of ITER in the ELMy H-mode scenario?

$D = 500/(1800+500) \times 100\% \approx 21.74$ %, so a maximum burn duty cycle of 21.74 %

(b) What is the minimum duty cycle related to the reset (i.e. everything that is happening in between two burn phases) in the ELMy H-mode scenario?

Reset duty cycle, so 1800 out of each (1800+500) s is used for the reset:
Reset duty cycle = $1800/(1800+500) \approx 78.26$ %
(Or reset duty cycle = 100% - burn duty cycle = 100 % – 21.74 % = 78.26 %)

(c) What are the maximum burn duty cycle and reset duty cycle of ITER in the extended ELMy H-mode scenario? Hint: do you expect the reset time to change?

The reset time stays the same, since only the operation scenario changes. Operation time is now 2000 s, while resetting the system costs 1800 s.
$D = 2000/(1800+2000) \times 100\% \approx 52.63$ %
Reset duty cycle = $1800/(1800+2000) \times 100\% \approx 47.37$ %
(Or reset duty cycle = 100% - burn duty cycle = 100 % – 52.63 % = 47.37 %)

(d) What are the burn duty cycle and reset duty cycle for a steady-state fusion reactor? And for a cyclic reactor with an 8-hour burn time?

A steady-state reactor can burn all the time (except for maintenance and repairs). So when it is running steady-state then it has a burn duty cycle D = 100% and no reset duty cycle.

When it is running with a very long burn phase of 8 hours, we still have a reset period. Assuming the reset period remains the same (1800 s):
$D = 8 \times 60 \times 60\text{s} / (1800 + 8 \times 60 \times 60\text{s}) = 94.12$ %
Reset duty cycle = 5.88 %

(e) What is the total reactor availability in both cases assuming that repairments account for 10% downtime?

Total reactor availability = availability × capacity factor, where:
availability = 90% (assuming 10% of the time for repairs); capacity factor = D/100

Total reactor availability (steady-state) = $0.9 \times 1 = 90\%$ of the time the reactor would be available

Total reactor availability (8 hour pulse) = $0.9 \times 0.9412 = 84.7$ % of the time the reactor would be available

Appendix C: Solutions to additional exercises v.1.0

Coming soon!