Nuclear energy as an imperative of the world development.
Nuclear fuel cycle and its relation to proliferation risk.

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Life is the struggle with entropy.

Basic statements about life and energy:

Any alive structure must belong to some global system where it consumes energy and releases heat and waste with the purpose to lower its own entropy level. Resulting entropy of the global system is always growing.

Living matter on Earth obtains energy from food and oxygen by means of their chemical transformation with release of appropriate form of energy.

Human being uses more energy than any other living entity since it reduces actively the entropy of its surroundings. Homo sapience is the only animal inventing special technologies to satisfy its energy needs.

One of the first technologies used by humans for energy supply was the cellulose oxidation, i.e. burning of wood. Surprisingly, after ages of progress in science and technology, the carbon burning still remains a dominant way to supply humans with energy!
Global energy needs

World energy consumption
and the history of technological revolutions and breakthroughs

Source: INEI RAS "Forecast of the development of the world's energy and Russia 2016"
Basic chemistry that Life uses for energy production:

The principle reaction of carbon atom oxidation:

\[ C + O_2 \rightarrow CO_2 + 4.2 \text{ eV} \]

or, for 1 mole:

\[ C + O_2 = CO_2 + 394 \text{ kJ} \]

Where the energy comes from?

About 85% of the energy used by people today is obtained by burning hydrocarbon fuel: oil, gas and coal - formed long ago as fossils. Another 10% is provided by hydropower and “renewables” (wind, photo-electric and biomass). All that energy is in fact the Sun radiation, either accumulated in the past or being transformed quite recently.

That is 95% of the energy we use today has its origin in the Sun.
Hydrocarbon primary sources produce energy by burning Oxygen and releasing CO₂ – “greenhouse gas”. In the modern world there is a growing conflict between energy needs and environment preservation.
Global energy needs

The renewable energy production: is it really environment friendly?

Are there any prospects for a breakthrough in existing energy technologies?

Conclusions from the INEI RAS research (2016) "Forecast of the development of the world's energy and Russia":

In the period up to 2040:
✓ There are no technological revolutions.
✓ Implementation of only technologies that are already being tested.
✓ Growth of economic efficiency of already applied technologies.
✓ Decrease in the energy intensity of the world's GDP.
Global annual energy consumption
in billion ($10^9$) tons of oil equivalent (toe)

<table>
<thead>
<tr>
<th></th>
<th>2019</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total primary energy consumed in 1 year</td>
<td>14</td>
<td>~ 20</td>
</tr>
<tr>
<td>Including the energy spent on electricity production</td>
<td>6</td>
<td>~ 10</td>
</tr>
<tr>
<td>Electric Power Consumption</td>
<td>2</td>
<td>~ 5</td>
</tr>
</tbody>
</table>

By the end of this century every year we may need up to 100 billion ($\sim 10^{11}$) toe of primary energy
Global energy needs

Facts about Energy

• By 2050 the people on our planet will be ready to consume every year about 20 billion \((10^9)\) toe (tons of oil equivalent) of primary energy.

• Today out of the total energy consumed by the people on Earth the electricity is not a major part, being behind the fuels directly burnt for heat production and transportation.

• Electricity demand is increasing twice as fast as overall energy use.

• The world will need significantly increased energy supply in the future, especially cleanly-generated electricity.

• Today nuclear power provides about 11% of the world's electricity, and 18% of electricity in OECD countries.

• All major international reports on future energy supply suggest an increasing role for nuclear power as an environmentally benign way of producing reliable electricity on a large scale.
### Global energy needs.

#### Resources of primary energy

<table>
<thead>
<tr>
<th>Energy class</th>
<th>Source type</th>
<th>Energy nature</th>
<th>Resource potential (toe)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrocarbon</strong> (fossil organic matter)</td>
<td>Oil</td>
<td>Transformed energy of the Sun accumulated by the relic plants. Released in a chemical reaction: ( \text{C} + \text{O}_2 \Rightarrow \text{CO}_2 + 4.2 \text{eV} )</td>
<td>(~10^{14}) (total)</td>
</tr>
<tr>
<td></td>
<td>Coal</td>
<td></td>
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<tr>
<td></td>
<td>Gas</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Methane hydrates</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Renewable</strong></td>
<td>Tidal energy (oceans)</td>
<td>Kinetic energy of the Earth rotation</td>
<td>(~10^{11}) (per year)</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydropower (rivers)</td>
<td>Radiation of the Sun</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geothermal energy</td>
<td>Compression of a proto-planetary cloud and heat of radio-isotope fission</td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>Nuclear power</td>
<td>( \text{n} + \text{U} \Rightarrow 200 \text{MeV}; \text{n} + \text{Th} \Rightarrow 200 \text{MeV} )</td>
<td>(~10^{19})</td>
</tr>
<tr>
<td></td>
<td>Fusion</td>
<td>( \text{d} + \text{d}, \text{d} + \text{t}, \text{d} + \text{He}^3 \Rightarrow 18+ \text{MeV} )</td>
<td>(&gt;10^{20})</td>
</tr>
</tbody>
</table>
Renewable energy potential

Hydropower

Wind

Solar

Geothermal

Tidal Energy

Biomass

Theoretical potential of all renewable energy sources: 180 billion (~2*10^{11}) toe per year
Solution of the 21st century energy problems requires the widespread use of nuclear energy.

In this century, public concerns will be focused much more than before on the environment problems which can not be solved effectively without nuclear power.

Potential of nuclear energy sources:
- Total for U and Th power reactors: $\sim 10^{19}$ toe
- Fusion power reactors: $> 10^{20}$ toe
Nuclear power in the world

Over the past 65 years nuclear power has become the reliable energy production technology with no emission of greenhouse gases into the atmosphere.

In 2018 there were 455 nuclear power units in the world with installed capacity 399,5 GW(e). 55 power units of 55,3 Mwe were under construction.
Nuclear power in the world

• Six countries (the United States, France, Japan, Russia, Germany, China) produce 75% of the world's nuclear power.

• **Light water reactors** of three types (PWR, BWR, VVER) constitute 80% of the world's nuclear power reactor park.

• Five countries have advanced developments in **fast reactors** (Russia, France, Japan, China, India).

• Five companies in 8 countries (TVEL, URENCO, AREVA, CNNC, JNFL) conduct commercial **enrichment of uranium**.

• Six countries (France, Great Britain, Russia, Japan, India, China) have nuclear fuel **reprocessing** facilities.

• 33 countries operate nuclear power plants.

• more than 10 other countries are building or plan to build NPPs on their territory.
Emergence of Nuclear Power

1938 – Nuclear fission of heavy elements was discovered by Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in 1939 by Lisa Meitner and Otto Robert Frish. They bombarded the nucleus of a uranium atom with neutrons, causing it to split and release energy.

This phenomena is called a stimulated nuclear fission and is in the basis of all contemporary nuclear power.
1939 – Leo Szilárd and Enrico Fermi searched for, and discovered, neutron multiplication in uranium, proving that a nuclear chain reaction by this mechanism was indeed possible. In this reaction, a neutron plus a fissionable atom causes a fission resulting in a number of new neutrons.

Energy released by 1 gram of carbon through burning equals $8.9 \times 10^{-3}$ KWh. Energy released by 1 gram of uranium-235 through fission equals $2.2 \times 10^4$ KWh.
Emergence of Nuclear Power

First NPP in the world - 1954, USSR, Obninsk, 5MWe.

First commercial NPP - 1956, Calder Hall, Cumbria, England, 60MWe.

The Shippingport reactor was the first full-scale PWR nuclear power plant in the United States, 1958, 60MWe.
Emergence of Nuclear Power

Operation of nuclear power plants in XX century has demonstrated:
- their high potential in meeting the energy needs of mankind;
- their advantages, particularly the absence of CO\textsubscript{2} emissions and other environmentally harmful effects, the stable and reliable operation.

In the same time there was permanent public concern in regard to nuclear power due to the following factors:
- historic association of atomic energy with nuclear weapons use by the USA at the end of the WW II;
- high educational barrier for public understanding and acceptance of this new technology, lack of public information effort on the part of the industry and governments;
- hostile activities of the nuclear power opponents, including greatly distorted information about nuclear accidents.

By the end of the century the attitude started to change in favor of nuclear power thanks to greater openness of the industry, growth of international organizations, greater support of nuclear industry by the governments and public bodies, etc.
What is the nuclear power fuel cycle?

The *nuclear fuel cycle* is the series of all industrial processes that involve the nuclear fuel manufacturing and production of electricity from nuclear fuel in nuclear power reactors. NFC conventionally described as consisting of the following two parts: “front end” including mining, ore processing, conversion, enrichment, fabrication; “back end” – post reactor spent fuel and radwaste management.
Nuclear Fuel Cycle Stages

*Uranium Mine* - Uranium *mining* is the process of extraction of uranium ore from the ground.

**Underground mining**

*Open pit*

*In situ leaching mine*
**Nuclear Fuel Cycle Stages**

*Milling* is a process of uranium recovery used to extract uranium from the ore. A conventional *uranium mill* is a chemical plant that extracts uranium using certain processes. When the uranium leaves a uranium mill, it is in the form of uranium compounds mixture, or what is commonly called *yellowcake* or *uranium concentrate* containing mostly oxide $\text{U}_3\text{O}_8$.

After the $\text{U}_3\text{O}_8$ is produced, the next step is *conversion* into pure *uranium hexafluoride* ($\text{UF}_6$). Uranium *enrichment* requires natural uranium in form of $\text{UF}_6$. That transformation is achieved at conversion plants.
Natural uranium is a mixture of two isotopes: uranium-238 and uranium-235. Enriched uranium is a kind of uranium in which the percent composition of uranium-235 isotope has been increased from natural 0.7% through the process of isotope separation. According to internationally accepted convention it is determined that enriched uranium with a lower than 20% concentration of U-235 is a low-enriched uranium (LEU). For use in commercial light water reactors (LWR), the most prevalent power reactors in the world, uranium is enriched to 3 to 5 % U-235.
Where there is a proliferation risk?

At the nuclear fuel cycle production chain the two **fissile** materials could be made that are sensitive from the point of view of possibility to be used for nuclear weapon manufacture:

- highly enriched uranium (HEU)
- plutonium (Pu).

HEU can be produced at the **front end** of NFC, Pu – at the **back end**. HEU production is done at the *enrichment* facility. Plutonium is obtained at the *reprocessing* stage.

Both materials could be used to manufacture of a **fission** type nuclear explosive – “atomic bomb”.

Nuclear power fuel cycle is not a source of principal materials for **fusion** type explosive - “hydrogen bomb”. However, fission reaction is needed to start fusion reaction, that is, to initiate the hydrogen weapon.
Highly enriched uranium (HEU) has a greater than 20% concentration of U-235 or U-233. The fissile uranium containing 85% or more of U-235 is known as weapons-grade uranium, although for a crude, inefficient weapon 20% is sufficient. The critical mass for 85% highly enriched uranium is about 50 kilograms, which at normal density would be a sphere less than 20 cm in diameter. HEU is also used in fast neutron reactors, research reactors as well as in naval reactors, where it contains at least 50% U-235, but typically does not exceed 90%.
Nuclear Fuel Cycle Stages

Nuclear Fuel *fabrication* is the final stage in nuclear fuel preparation prior to use in a reactor. Fabrication involves chemical transformation of UF₆ into oxide UO₂ (the *powder*), manufacturing from it the *pellets*, fabrication of the fuel *rods*. The finished fuel rods are grouped into fuel *assemblies* that are used to build up the *core* of a power reactor.
Nuclear Fuel Cycle Stages

Graphic courtesy Argonne National Lab and Nuclear Energy Institute
Nuclear Fuel Cycle Stages

Spent nuclear fuel, occasionally called used nuclear fuel, is nuclear fuel that has been irradiated in a nuclear reactor.

Spent nuclear fuel “dry” storage

Nuclear reprocessing technology was developed to chemically separate and recover fissionable plutonium and uranium from irradiated nuclear fuel.
Radioactive waste is the waste that contains radioactive material. Radwaste is usually a by-product of nuclear power generation and other applications of nuclear technology, such as research and medicine. Radioactive waste because of ionizing radiation it produces is hazardous to most forms of life and the environment, and is regulated by government agencies in order to protect human health and the environment.

The radwaste could be Low-level and High-level. Low-level waste includes items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. High-level radioactive wastes are the highly radioactive materials produced as a byproduct of the reactions that occur inside nuclear reactors.
Nuclear Fuel Cycle Stages

The radioactive waste *disposal* is especially important for high active waste. The time frame in question when dealing with radioactive waste ranges from 10,000 to 1,000,000 years. One of disposal methods currently used is a geologic disposal. The problem on waste disposal is one of the most troubling for the people and the one where new technologies are being developed.

Yucca Mountain, USA: nuclear waste repository, never finished
Market for these products and services has an over 40-year long history:

- 1950-60s – establishing the industry, no market yet, the USA dominates
- 1970s – new players come, market arises
- 1980s – market rules and regulations emerge
- 1990-2000s – market matures
- 2010s – new challenges: expectations and disappointments (“nuclear renaissance”, Fukushima)

Front-end products and services traded on the international market:

- natural uranium – \( \text{U}_3\text{O}_8 \)
- conversion to \( \text{UF}_6 \)
- isotopic enrichment - SWU
- low enriched uranium
- fabrication services
- complete fuel assembly
NFC Market Regulation System

Proliferation risks are associated mostly with enrichment and LEU. Therefore all circulations of nuclear front-end products and services are subject to international and national safeguards systems. Those systems operate in all countries involved in nuclear power development.

Legal framework
- ✓ WTO (general rules for power resources trade)
- ✓ Non-Proliferation Treaty and regional agreements
- ✓ Nuclear Suppliers Group and Zangger Committee
- ✓ Bilateral “123” Agreements
- ✓ National regulations and legislation

Regulation bodies
- ✓ International (IAEA, Euratom)
- ✓ National authorities (export control, customs regulation, etc.)
NFC Market Regulation System

Nuclear materials management system in Russian Federation:

- Federal Service under Technical & Export Control (*nuclear trade licensing*);
- Federal Customs Service;
- Federal Service for Ecological, Technological and Nuclear Supervision;
- Law enforcement bodies.

Future nuclear power development must lead to creation of the *international market of back-end* products and services. Russian Federation has all technological and legal infrastructure for that and is already making “complex commercial offers” for NPP construction projects including nuclear reactors supplies together with front-end and back-end services. Examples: NPPs supplied to Iran, India, projects in Turkey, Egypt.
NPP and nuclear reactors market

Challenges for nuclear power development:

- Economics.
- Used fuel and high level waste management.
- Nuclear fuel resources.
- Nuclear safety and nuclear security.
- Nuclear non-proliferation.

Current reactor development by major vendors:

**Advanced PWR and BWR:**
AES-2006 or VVER-1200 TOI, VBER, VVER-600 (Russia),
AP-1000 (USA, Japan, China), EPR-1600 (France),
ABWR (Japan, USA)

**Advanced CANDU type reactors:**
ACR-1000 (Canada), AHWR (India)
The project NPP AES-2006 is a third plus generation evolutionary pressurized water reactor based on Russian VVER-1000 plants. Electric power – 1200 MW.

The first of two units of VVER-1200 was commissioned in 2016 and started industrial operation at Novovoronezh-2 site in February 2017. Work is underway on construction of two VVER-1200 units at the Leningrad-2 site.
Safety features of AES 2006 – VVER-1200

Hurricanes, tornadoes
max. design wind velocity: 56 m/s.

Shock wave with the front pressure of 30 kPa

Seismic impacts
Basic option: SSE – intensity 7 on the MSK-64 scale
DBE – intensity 6

Aircraft fall
Basic option: 20 tons.
Option: 400 tons.

Floods, storms
according to site-specific conditions
Rosatom’s new VVER projects outside Russia

- Brazil: 4 projects
- Argentina: 2 projects
- Bulgaria: 2 projects
- Czech Republic: 2 projects
- Slovakia: 2 projects
- Hungary: 2 projects
- Turkey: 4 projects
- Finland: 1 project
- Belarus: 2 projects
- Ukraine: 2 projects
- Kazakhstan: 2 projects
- Armenia: 2 projects
- Jordan: 2 projects
- Saudi Arabia: 2 projects
- India: 2 projects
- Bangladesh: 2 projects
- Vietnam: 2 projects
- Malaysia: 2 projects
- Indonesia: 2 projects

Legend:
- Green: Construction or site preparation
- Yellow: Tendering or negotiations
- Blue: Prepared under governmental contract
- Red: Potential

Total: 52 projects
Rosatom new projects

Rosatom has commissioned 13 new nuclear power units over the last 11 years, in China, India, Iran and Russia. Its current VVER portfolio includes 35 units. It has 60 units in operation and 41 at the project implementation stage. Novovoronezh II-1 - Rosatom’s first Gen III+ VVER Design - started commercial operation last year, and its second, Leningrad II-1 was grid connected this year.

Rosatom commissioned the BN-800 fast neutron reactor at the Beloyarsk nuclear power plant in 2015 and is nearing completion of the design of the “next Step” fast reactor BN-1200.

Small modular reactor technology is being developed as “a truly innovative solution” both on land and at sea. Rosatom has 400 reactor years of experience in nuclear icebreakers, and its Akademik Lomonosov this year became the world’s first floating nuclear power plant to be commissioned. Rosatom also commissioned the new nuclear icebreaker Arktika, the first of three vessels of Project 22220 which will be able to break through ice 3 meters thick as they escort vessels across the Arctic Ocean.
Annex: On the relation between proliferation risk, needs in nuclear power and ownership of uranium enrichment capacity.

Economic estimates show that to own enrichment plant compared to purchasing the separation work in the world market becomes profitable if the enrichment service is in demand by nuclear power plants with a total capacity of about 10-12 GW, that is by 10 to 12 typical nuclear power units. Then the annual production of the enrichment plant intended for local consumption must be 1.5 - 2 million SWU. This evaluation is qualitatively shown in the diagram below.

Dependence of cost on time in two cases: plant construction and operation cost (1) or buying SWU on the market (2): a) for 1 nuclear reactor; b) for 6 reactors, and c) for 11 reactors.

Sources

5. https://www.nei.org/News-Media/News/Milestones