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Einstein's Equation in Nuclear and Solar Energy

Ancuta M. Magurean, Octavian G. Pop, Adrian G. Pocola, Alexandru Serban and Mugur C. Balan

Abstract

Starting from the equation of Einstein ($E = m \cdot c^2$), the chapter proposes a simple and fundamental presentation of the fission and fusion principles, together with some of their applications: nuclear reactors and nuclear propulsion vessels and submarines. Fission and fusion are chosen between the multiple forms of energy, as being the most important forms of nuclear energy, directly related with the equation of Einstein. Some characteristics of solar energy, produced from the fusion process inside the Sun, are deducted from the same equation of Einstein: thermal power of solar radiation; specific power of solar radiation; surface temperature of the Sun; solar constant on different planets, etc. The yearly variation of the solar radiation on each planet of the solar system is also presented.

Keywords: Einstein equation, fission, fusion, solar energy, solar constant, solar radiation

1. Introduction

The energy is a form of a manifestation of matter in motion, the widely used definition of which is that the energy of a system is its capacity to perform mechanical work, when it passes from an existing state to a reference state [1, 2].

The energy, as defined in the literature, as well as on numerous websites, in various languages of international circulation, is the ability of a physical system to produce mechanical work [3].

Occasionally it is mentioned in the definition of energy, the capacity of a physical system to produce heat, as well.

However, these definitions refer only to the production or conversion of mechanical work or heat, but these represent only two of the many forms of existing energy [4].

The notion of energy is much more complex being obviously associated with other systems besides the physical ones, namely, biological and chemical systems, etc. [5].

Sometimes the literature considers that the energy is involved in all processes that require any kind of change or conversion, being responsible for the production of those changes [6].

It can be even considered that the matter itself is a “condensed” form of energy and that energy is stored in the atoms and molecules of which matter is composed [7–9].

The goal of the study is to investigate the connections between the fission, fusion, and solar energy through Einstein's equation.

2. Einstein's equation

The connection between energy and matter is represented by Albert Einstein's famous equation introduced as [10]:

$$E = m \cdot c^2 \quad (1)$$

where E is the energy; m is the mass; c is the speed of light.

Albert Einstein was a theoretical physicist of Jewish ethnicity, which was born in Germany, stateless since 1896 and later Swiss citizen, in 1899. He immigrated in 1933 to the USA, being naturalized as an American citizen in 1940. He was a university professor at Berlin and Princeton, and he is the author of the theory of relativity and one of the brightest scientists of mankind. In 1921 he was awarded with the Nobel Prize in Physics.

The above relationship could be associated with the beginning of the universe and, at least on an empirical level, can support the theory of the appearance of matter in the universe, when after the original explosion (called the "Big Bang"), an enormous amount of energy was transformed into matter. This process can also be correlated with the so-called "information preservation" principle, which in a simplified way shows that evolutionary processes cannot create the information required to generate biological evolution. The law of information preservation was enunciated by biologist Peter Medawar in his work *The Limits of Science*, in 1984 [11].

Through various processes, the high amount of energy contained in the atoms (especially in the nuclei) can be released and used for various purposes, and as a result of these processes, the matter which is used as an "energy source" is significantly transformed.

Two of the most representative examples of these types of transformations are the production of energy by nuclear fission (the break of element nuclei), respectively, and by nuclear fusion (the recombination and joint of element nuclei).

Both processes are accompanied by matter conversions into high amounts of energy.

Fusion is even the energy source of the stars, of which category the Sun belongs.

Both the fission and the fusion are characterized by the breakage of some types of bonds, existing initially at the level of the nuclei and the construction of other types of bonds, in the new nuclei formed as a result of these processes.

It is mentioned that iron (Fe) and nickel (Ni) are the chemical elements which have the highest breaking energies of the nucleus. In other words, for these two elements, the greatest amount of energy must be consumed for breaking the nucleus. The nuclei of all other elements "break" more easily [12].

3. Einstein's equation and the nuclear fission

Nuclear fission is a nuclear reaction or a process of radioactive decay, after which the atomic nucleus splits into lighter nuclei.

Usually, through the fission (breaking/disintegration) of nuclei heavier than iron, more energy than is necessary to maintain the cohesion of the newly formed (lighter) nuclei is released. Consequently, through the fission of "heavy" nuclei, energy can be obtained.

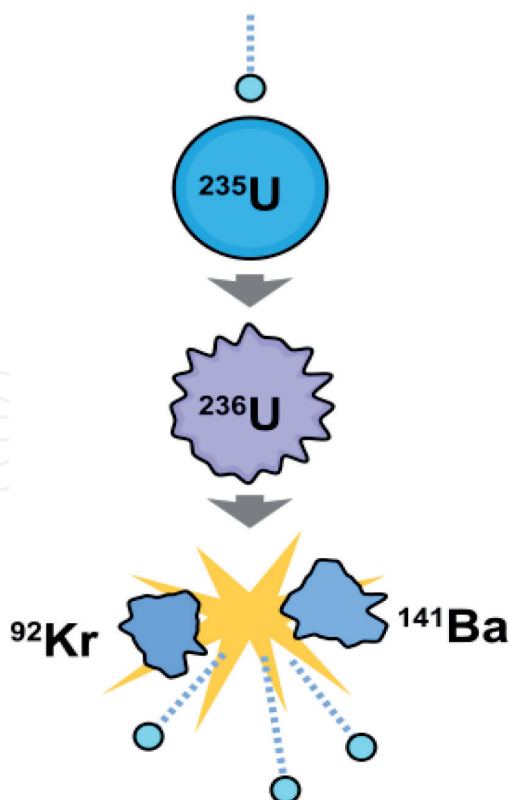


Figure 1.
 Scheme of the fission reaction of uranium in krypton and barium (https://en.wikipedia.org/wiki/File:Nuclear_fission.svg).

Note: For the fission of nuclei lighter than iron, in order to maintain the cohesion of the newly formed nuclei, more energy is required than can be released through “the break” of the initially existing nucleus. Therefore, for the fission of light nuclei, energy input from the outside is required.

Usually, the fission results in nuclei with close mass, the ratio of the masses of the nuclei formed by fission being of maximum 2 or 3 [13].

Nuclear fission of heavy elements was discovered in 1938 by Lise Meitner, Otto Hahn, Fritz Strassmann, and Otto Robert Frisch [14, 15].

Modern fission, artificially produced, is usually initiated using a neutron that is “embedded” in a nucleus and disrupts its balance.

The energy released in fission reaction was calculated for the first time in [16].

Figure 1 shows a scheme of the induced fission reaction to uranium, a reaction used in nuclear power plants.

• **Comments:**

- The kinetic energy of the neutron absorbed by the U235 nucleus causes the formation of the U236 nucleus, which is unstable and fragment (fission) in Kr92 and Ba141.
- Following the reaction, in addition to Kr92 and Ba141, three neutrons, Γ (gamma) radiation (not shown in the figure), and a very large amount of energy are obtained.
- Instead of uranium, various plutonium isotopes can be used as fuel.
- The presence of gamma radiation requires the protection of the nuclear reactor against the emission of radiation of this type, since they are harmful to life.

The energy released in the fission reaction can be calculated with Einstein's Eq. $E = \Delta m \cdot c^2$, where Δm is the mass difference in the mass difference after the fission [17].

The most important applications of fission are:

- Electricity generation (in nuclear power plants).
- Propulsion of ships and submarines.

Figure 2 shows the scheme of a nuclear power plant.

The Romanian nuclear power plant from Cernavodă was designed with five reactors, of which only two are currently operating, each with a net power of ≈ 655 MW, respectively, and a total capacity of 706 MW. Currently, this plant provides approx. 18% of Romania's electricity demand.

The nuclear power plant from Cernavodă is CANDU type, a name derived from "Canada Deuterium Uranium." The reactor uses natural uranium (0.7% U^{235}) as fuel, respectively, and heavy water (D_2O) as neutron moderator and primary cooling agent. The notion of "neutron moderator" refers to the lagging of neutrons resulting from fission (thermal neutrons), in order to increase their efficiency in producing new fission reactions. CANDU reactor technology has been used in all nuclear power plants in Canada and in countries such as India, Pakistan, Argentina, South Korea, China, and Romania.

The scheme of the CANDU reactor is shown in **Figure 3**.

Figure 4 shows the first nuclear-powered aircraft carrier, undertaken by fission. This is the USS Enterprise aircraft carrier, built in 1964, currently decommissioned (since December 1, 2012), which has remained the longest ship in the world (342 m) to date, followed by the 10 US aircraft carriers in the "Nimitz" class, manufactured between 1975 and 2009 (333 m).

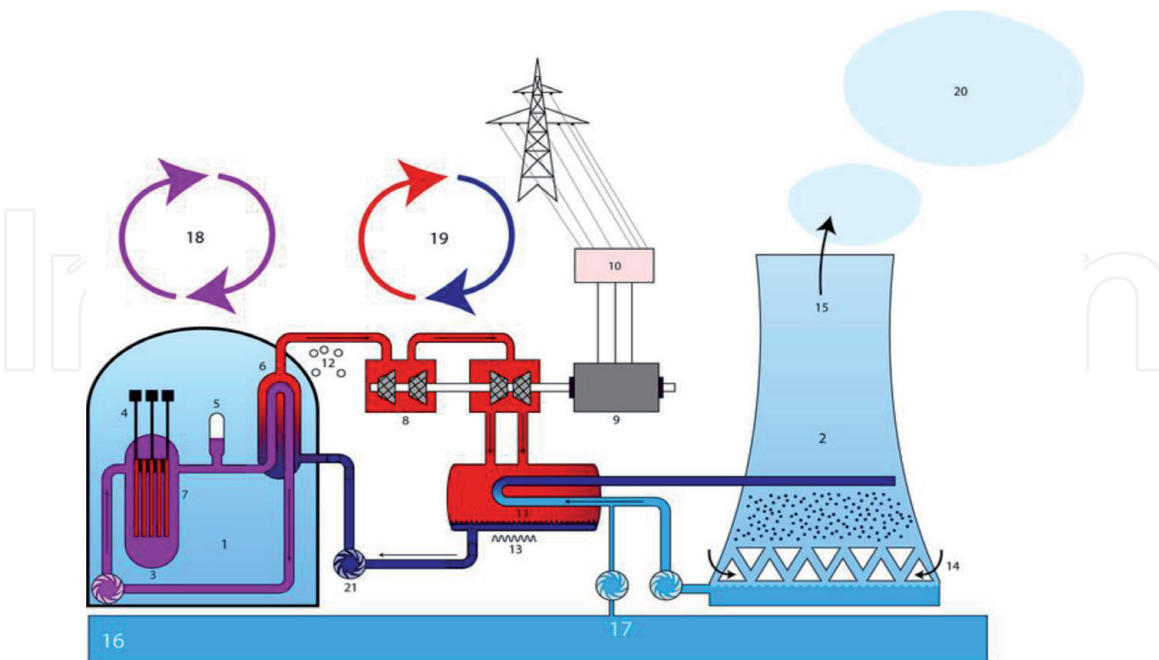


Figure 2.

Schematic diagram of a nuclear power plant (http://commons.wikimedia.org/wiki/File:Nuclear_power_plant-pressurized_water_reactor-PWR.png). 1, reactor block; 2, cooling tower; 3, reactor; 4, control rods (fission inhibitor); 5, pressurized tank for the primary coolant; 6, steam generator; 7, fuel bars; 8, turbines; 9, electric generator; 10, high voltage transformer; 11, condenser; 12, steam; 13, condensate; 14, cooling air; 15, hot air with high humidity; 16, water source; 17, cooling water outlet; 18, primary circuit (heavy water D_2O in the case of natural/enriched uranium used as fuel); 19, secondary circuit (water H_2O); 20, water vapor evacuated into the air; 21, recirculation pump.

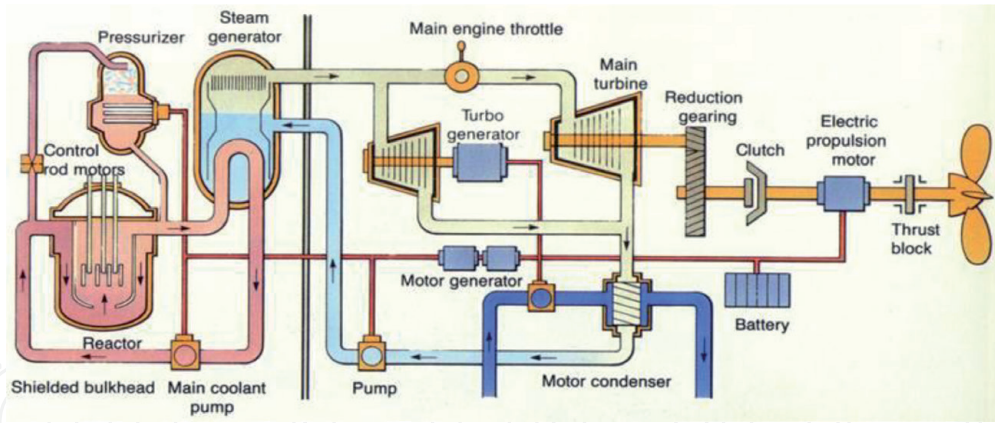


Figure 5. Scheme of the nuclear propulsion system of ships and submarines (http://www.subadventures.net/Sub_04_719_files/image018.jpg).

- A list of the longest ships in the world is available on the Internet: http://en.wikipedia.org/wiki/List_of_longest_naval_ships.
- The inscription on the main deck was made by the aircraft carrier's crew to mark 40 years of naval nuclear propulsion.
- The aircraft carrier USS Enterprise was decommissioned due to the long period of operation of the nuclear propulsion system and due to the equipment on the main deck, which allowed the radar position to be detected on the aircraft carrier. The aircraft carriers of the "Nimitz" class are of "stealth" type (hidden or not detectable on the radar).

Figure 5 presents the scheme of operation for the nuclear propulsion system of ships and submarines.

4. Einstein's equation and the nuclear fusion

Nuclear fusion is a nuclear reaction that causes two or more nuclei to collide at very high speeds and merge to form a new type of atomic nucleus. Sometimes, the energy needed to initiate this process is provided by a very high "working" pressure (e.g., inside the stars this pressure is provided by the gravity determined by their mass).

By fusion (the union of nuclei) easier than iron, more energy than is necessary is produced, in order to form bonds for the newly formed nucleus. As a result, by the fusion of "light" nuclei, energy can be obtained.

Note: For fusion of nuclei heavier than iron, in order to achieve the necessary connections to maintain the cohesion of new nuclei, external energy contribution (consumption) is required.

Figure 6 shows a scheme of the fusion reaction between a deuterium atom (H^2) and a tritium atom (H^3), after which a helium (He^4) atom is formed. From the reaction also results a neutron.

The amount of energy produced is $17.59 \text{ MeV} = 2.8 \cdot 10^{-12} \text{ J}$, which is in agreement with Einstein's equation, considering the equivalent loss of mass as a result of the fusion reaction [18–20].

The only application of the artificially produced fusion is the hydrogen bomb.

Figure 7 shows the explosion of the first hydrogen bomb, whose code name was "Ivy Mike" (November 1, 1952).

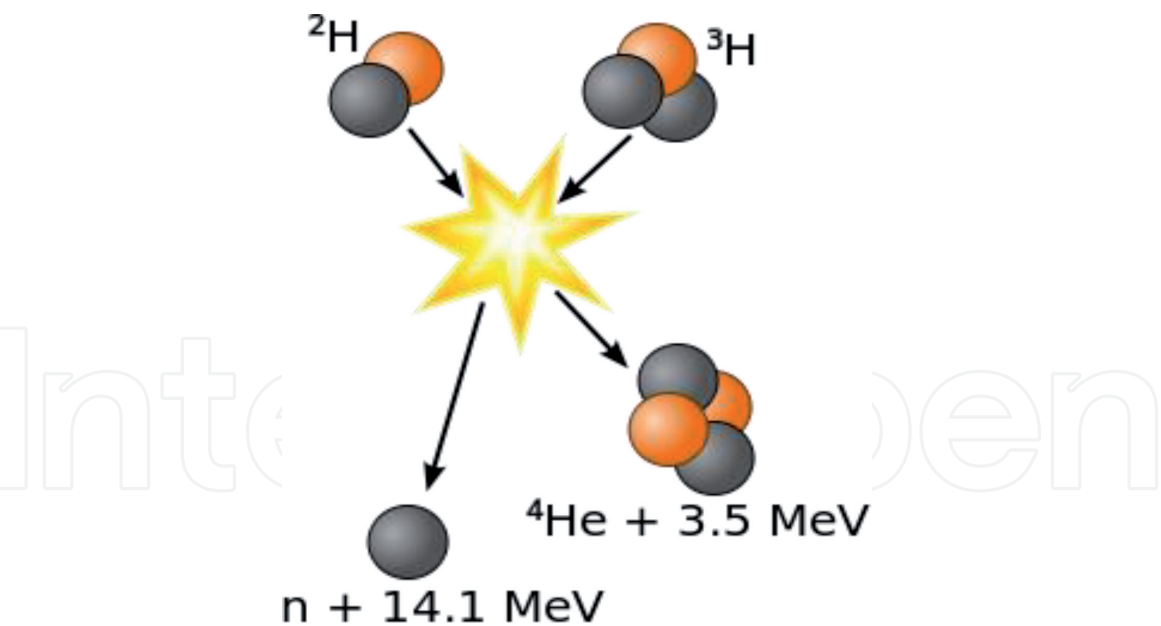


Figure 6.
Scheme of the fusion reaction between deuterium and tritium (https://en.wikipedia.org/wiki/File:Deuterium-tritium_fusion.svg).



Figure 7.
Explosion of the first hydrogen bomb (<https://en.wikipedia.org/wiki/File:IvyMike2.jpg>).

One of the most important scientific research projects, which aim to obtain energy through fusion, for peaceful use, is the International Thermonuclear Experimental Reactor (ITER) [21].

The project is carried out in collaboration with many countries: European Union countries, the USA, Japan, Russia, China, South Korea, and India.

Figure 8 presents the small-scale model of the ITER fusion reactor.

The ITER fusion reactor was designed to produce 500 MW of final energy and will consume approx. 50 MW to ensure its own energy consumption.

The construction of the ITER complex began in 2013, with the cost of construction now reaching \$ 16 billion USD, almost three times more than originally expected.

The infrastructure is expected to be completed in 2025, the commissioning of the reactor to be completed in the same year, as well. Plasma experiments should start in 2025, and deuterium-tritium fusion experiments should begin in 2027.

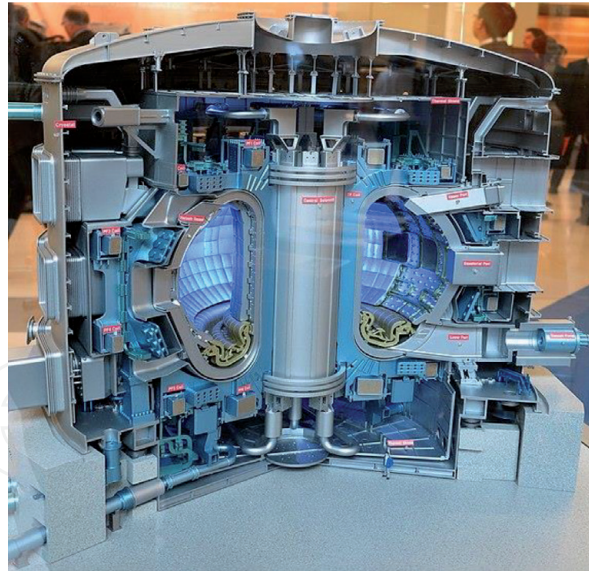


Figure 8.

Small-scale model of ITER (https://upload.wikimedia.org/wikipedia/commons/thumb/7/75/ITER_Exhibit_%2801810402%29_%2812219071813%29_%28cropped%29.jpg/250px-ITER_Exhibit_%2801810402%29_%2812219071813%29_%28cropped%29.jpg).

The project contributes to the implementation of the results obtained in decades of research, in an experimental installation, which will allow the transition to a commercial installation.

5. Einstein's equation and the solar energy

The most representative example of fusion is represented by the reactions inside the Sun.

The Sun represents the energy source of the Earth [22], contributing to maintain the planet's temperature well above the value of almost 0 K, encountered in the interplanetary space and is the only source of energy capable to sustain life on Earth [23].

The Sun can be considered as a sphere with a diameter of approximately 1.4 million km, more precisely 1.39×10^9 m [24], at a distance of approx. 150 million km from the Earth, 1.5×10^{11} m [24]. This distance is so high that two straight lines that start from one point on the Earth's surface to two diametrically opposite points on the solar disk form an angle of approximately half a degree. Under these conditions, although solar radiation is emitted in all directions, it can be considered that the solar rays that reach the Earth's surface are parallel [25].

In the core of the Sun, continuous nuclear fusion reactions occur, by which hydrogen is converted into helium. Currently, the mass composition of the Sun is approx. 71% hydrogen, 27.1% helium, 0.97% oxygen, and other elements in lower concentrations [26].

The rate of conversion of hydrogen into helium is approx. 4.26 million tons per second [27, 28]. This flow of substance is continuously transformed into energy. It is estimated that at this rate, in the next 10 million years, approximately 1% of the current amount of hydrogen will be consumed, so there is no imminent danger of depletion of the Sun's energy source. The lifetime of the Sun is estimated at approximately 4–5 billion years.

Considering the mass flow of solar substance that is consumed continuously turning into energy $m = 4.26$ million t/s $= 4.26 \cdot 10^9$ kg/s, the thermal power of the solar radiation emitted as a result of this process (P) can be calculated starting from the famous equation of Einstein for energy calculation (E):

$$E = m \cdot c^2 \text{ [J]}; P = \dot{m} \cdot c^2 \text{ [W]}. \quad (2)$$

where $c = 300,000 \text{ km/s} = 3 \cdot 10^8 \text{ m/s}$ is the speed of light.

Substituting the relation of the thermal power of the radiation emitted by the Sun, we obtain:

$$P = 4.26 \cdot 10^9 \cdot 3^2 \cdot 10^{8 \cdot 2} = 38.34 \cdot 10^{25} \text{ W}. \quad (3)$$

The specific power of the radiation emitted by the Sun (P_S), representing the power of the radiation emitted by the surface unit, can be calculated with the relation:

$$P_S = P/S_S \text{ [W/m}^2\text{]}. \quad (4)$$

where $S_S = 6.08 \cdot 10^{12} \text{ km}^2 = 6.08 \cdot 10^{18} \text{ m}^2$ is the total surface area of the Sun.

Replacing it, we obtain:

$$P_S = 38.34 \cdot 10^{25} / 6.08 \cdot 10^{18} = 63.059 \cdot 10^6 \text{ W/m}^2 = 63.059 \text{ MW/m}^2. \quad (5)$$

For comparison, it is mentioned that the maximum power developed by the Renault engine K7M (1.6 MPI), which equips some models of the Renault Group cars, is 64 kW, at a maximum speed of 5500 rpm. Thus, the specific power of the radiation emitted by the Sun (P_S) is approximately equivalent to that of 1000 engines that equip these cars, which operate at maximum speed. Considering that the length of a car is 4.25 m, those 1000 cars placed one after the other, in a straight line, "bar to bar" would stretch 4.25 km. Also for comparison, the net power of a nuclear reactor from Cernavodă (655 MW) represents about 10 times more than the specific power of the radiation emitted by the Sun (63 MW/m^2). In other words, every square meter of the Sun's surface emits energy characterized by a thermal power approximately equivalent to one tenth of the power of a reactor from Cernavodă.

Since the Sun emits radiation over all wavelengths, it can be considered an absolute black body [29, 30], and the power emitted in the unit of time, on the surface unit, by an absolute black body (P_S) depends only on its temperature and can be calculated according to Boltzmann's law, with the relation:

$$P_S = \sigma \cdot T^4 \text{ [W/m}^2\text{]}. \quad (6)$$

where σ is Boltzmann's constant: $\sigma = 5.67 \cdot 10^{-8} \text{ [W/m}^2\text{K}^4\text{]}$; T is the absolute temperature of the black body (of the Sun) [K].

Using the above relationship, the value of the Sun's surface temperature can be determined as:

$$T = \sqrt[4]{\frac{P_S}{\sigma}} \text{ [K]} \quad (7)$$

Replacing it, we obtain $T = 5774 \text{ K} \approx 5500^\circ\text{C}$.

This value corresponds to that indicated by most bibliographic sources, which also confirms that all undertaken calculations are correct.

The core temperature of the Sun is estimated to vary between $(8 \text{ and } 40) \cdot 10^6 \text{ K}$ [14].

It can be considered that the solar radiation is emitted uniformly in all directions and can be found throughout the solar system. The intensity of the available solar radiation due to this mechanism obviously depends on the distance to the Sun, and

the thermal power of the solar radiation is evenly distributed on spherical surfaces, with the Sun in the center.

On these considerations, the thermal power of the radiation emitted by the Sun ($P = 38.34 \cdot 10^{25} \text{ W}$) can be calculated with the relation:

$$P = I_S \cdot S_S \text{ [W]}. \tag{8}$$

where $I_S \text{ [W/m}^2\text{]}$ is the intensity of radiation available on the surface unit of a sphere with the Sun in the center; $S_S \text{ [m}^2\text{]}$ is the surface of the sphere on which the intensity of the solar radiation is calculated.

By using the relation presented above, the intensity of the solar radiation related to the surface unit of a sphere having the Sun in the center (I_S) can be calculated with the relation:

$$I_S = P/S_S \text{ [W/m}^2\text{]}. \tag{9}$$

where $S_S = 4 \cdot \pi \cdot D^2 \text{ [m}^2\text{]}$.

Replacing it in the previous relationship, we obtain:

$$I_S = P/(4 \cdot \pi \cdot D^2). \tag{10}$$

Thus, the intensity of the available solar radiation at the upper limit of the Earth's atmosphere can be calculated using the previous relation, considering that D is the distance between the Earth and Sun and $D = 149,597,871 \text{ km} = 1.496 \cdot 10^8 \text{ km} = 1.496 \cdot 10^{11} \text{ m}$:

$$I_S = 38.34 \cdot 10^{25} / (4 \cdot \pi \cdot 1.1496^2 \cdot 10^{11.2}) = 1.364 \cdot 10^3 \text{ W/m}^2. \tag{11}$$

The intensity of the available solar radiation at the upper limit of the Earth's atmosphere is referred to as the solar constant [31].

The value of the solar constant calculated previously corresponds to the value adopted by the World Radiation Center, of 1367 W/m^2 . This value is also reported by numerous bibliographic sources. The value of the solar constant, which is determined by measurements undertaken by satellites, underwent several corrections over time, as can be seen in **Table 1**.

The value of the available solar radiation at the upper limit of the terrestrial atmosphere suffers throughout the year small variations of approx. $\pm 3\%$, mainly due to fluctuations in the distance between the Earth and the Sun [24].

Value [W/m ²]	Year	Author	Ref.
1323	1940	Moon	[32]
1355	1952	Aldrich and Hoover	[33]
1396	1954	Johnson	[31]
1353 \pm 1.5%	1971	NASA	[34]
1373 \pm 2%	1977	Frohlich	[35]
1368	1981	Willson	[36]
1367–1374	1982	Duncan et al.	[37]
1367 \pm 1%	—	World Radiation Center	[24]

Table 1.
Accepted values over time for the solar constant.

6. Conclusions

Even if nuclear and solar energies seem to be different domains, the study proved that fission, fusion, and solar energy can be connected and have in common the famous equation of Einstein ($E = m \cdot c^2$).

Both in fission and fusion, the mass varies during the reactions, and it was highlighted that the mass variation and the released energy are related by the equation of Einstein.

The same equation was also applied to the mass flow of solar substance that is continuously consumed in the solar fusion reactions, and starting from this point, it was possible to calculate important parameters such as the energy and the power emitted by the sun.

Following this new approach, it was possible to determine the temperature of the sun's surface and the solar constant, both being in agreement with the values provided in literature.

It can be concluded that fission, fusion, and solar energy are linked together by the equation of Einstein.


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