Lars Jaeger

Ways Out of the Climate Catastrophe

Ingredients for a Sustainable Energy and Climate Policy

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Preface

Everyone has his or her own personal "aha" experience when it comes to climate change. Some have tried in vain with a hose and watering can to get their garden through several drought summers without damage. Others are surprised to be bitten at home by a tiger mosquito, which was originally only found in the tropics and subtropics. And yet, others have had to watch their houses being flooded because, for the first time in living memory, a small creek has become a torrential stream after a heavy rainfall event.

For me, climate change became painfully real when I hiked to the Morteratsch Glacier in the Upper Engadine in the summer of 2020, the largest glacier in the Swiss Eastern Alps. In the midst of the impressive mountain scenery, hikers can experience a dramatic event: where the hiking trail leads to the glacier tongue, which was once kilometres long and many hundreds of metres wide, signs provide information about the point reached by the ice in past decades. Since 1870, it has receded by an average of 18 metres every year, and in 2015 alone, the figure was as much as 164 metres! For more than two and a half kilometres, you walk on bedrock that was covered by dozens of metres of ice just the blink of an eye ago in geological history.

The fact is that climate change is no longer a threat on the horizon. It has arrived in our everyday lives and threatens our livelihoods. The main issues have been known since the 1980s: man-made greenhouse gases—above all carbon dioxide, CO_2—are causing our planet to heat up. At that time, concrete plans of action were already on the table, but a powerful industrial lobby prevented their implementation and deliberately undermined the reputation of the scientists involved.

Today, the picture looks very different. Those who take action against climate change are no longer marginalised. This is reflected by the almost entirely positive response to the "Fridays for Future" movement after initial criticism. What is more, politics and business are vying to outdo each other in their efforts to prevent the climate catastrophe. In autumn 2020, both the EU and China announced a roadmap to a CO_2-neutral economy by 2050 and 2060, respectively. Shortly afterwards, the German automotive industry also committed itself to this goal. And once Donald Trump was voted out of office, the USA followed suit.

After three and a half decades of stalemate, regression, and a few hard-won advances in the fight against climate change, it is now a game of dominoes: forces that resisted the global energy revolution that is hoped to save our climate are falling—one by one. Year after year, even the most optimistic forecasts about the possibilities of new technologies are caught up in and surpassed by current developments. There is no shortage of ideas, technological possibilities, and concrete initiatives. Almost all of them revolve around the central factor in climate change: energy. Apart from some aspects of agriculture, all the influences that humans have on the climate can be traced back to the way we produce and consume energy. Driven by the astonishing technological advances in the fields of photovoltaics, wind power, and battery energy storage, as well as nanotechnology and artificial intelligence, we are on the threshold of the fastest and most far-reaching revolution in the energy sector in the last 150 years!

This book aims to guide you through the world of energy and our planet's climate and provide facts:

- What is energy anyway?
- How do we produce, transport, and store energy?
- Why does our type of energy consumption influence the world's climate?
- How do scientists' climate models work, and can they really be trusted?
- What can we expect from technological progress?
- What possibilities do we have to produce energy without negative climate effects?
- Can we afford all this?

The answers given in this book refute the opinions of the few climate sceptics and deniers who still cause great confusion. The facts show: *Yes, we can!* The situation is very serious, but we are on the way to reversing the devastating climate trend—and this without any significant reduction in prosperity. After three decades of deep sleep and criminally missed opportunities, a promising dynamic has finally emerged. We have already achieved a lot on our way to climate neutrality—for example, in 2020, for the first time in Germany, the industrial and economic power house of Europe, more renewable than fossil power, was used. What matters now is that we do not run out of steam in the middle of this energy revolution, and that we continue to master the economic and political challenges that come with it. After all, our journey into a future free of greenhouse gases is well under way.

Baar, Switzerland Lars Jaeger
August 2021

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Many people have read this text and have made valuable suggestions for improvement. First of all, I would like to thank Bettina Burchardt, without whom the book in this form would not have been possible. In many hours, she has devoted herself to the text and its contents and has brought this book into the form it now has. I would also like to thank Angela Lahee at Springer for her support during the creation of this book. Thanks also to my agent, Mrs. Beate Riess, for all her support and encouragement, not only for this book, and likewise Mrs. Anne Katrin-Weise.

Despite all this help, there are sure to be some errors and numerous omissions. The subject matter is so vast and complex that it would not be possible to cover every aspect and/or every issue to the extent that it deserves to be covered. I naturally take full responsibility for this and urge the reader to consult the many specialist books on the subject.

Contents

Part II Climate

Part III Power

Part IV Society

Part I

Energy

1

From Aristotle to Nuclear Fusion: The Long Road to Understanding What Energy Actually Is

What exactly is energy? Today, the answer to this question is material for junior high school classes—and yet most people find it difficult to describe the phenomenon of energy in a physically correct way. Experience has shown that the terms force, power, momentum, and energy get quite easily confused. And even the scholars of the last 2500 years were for a long time unable to describe their observations with cleanly separated terms and thus bring order to this energy chaos. Therefore, right at the beginning of the book an overview: What is what?

1.1 In the Beginning Was the Force

"Why does a stone fly through the air when we throw it and not immediately fall vertically to the ground?" This question triggered probably the longest dispute in the history of the natural sciences. The father of physics, the Ancient Greek philosopher Aristotle, was convinced that forces only work when there is direct contact from body to body—in the same way that billiard balls, for example, move in new directions when they collide with each other. Because only air could be used as a carrier for a force acting on the stone, Aristotle put it this way: The stone displaces the air, which then rejoins behind it and pushes the stone forward so that it continues to fly straight ahead.

Like all Aristotle's explanations, his theory of movement was hardly questioned for two thousand years. Only in the late Middle Ages did European

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scholars begin to detach themselves from the ideas of the ancient thinkers. Now the "impetus theory" came into being. The scholar Johannes Philoponos had already developed its basic principles in the sixth century AD, but it had stood no chance against the dogma of Aristotle. The impetus theory states that an immaterial force, which is located *in the moving body*, determines its trajectory. When we throw the stone, the "impetus" is an inner drive that passes from the hand of the thrower to the stone and imparts its movement to it. For some scholars, the impetus theory had a theological dimension: just as a moving force is transferred from the thrower to the projectile, the host should also sustain a force that has been communicated by God.

The impetus theory broke completely with the Aristotelian tradition. But it too was far from the truth. Where in the moving body should the impetus be? And how should we imagine it? In addition, there was no way the actually observed movement of projectiles could be explained by the impetus.

It was Galileo and Newton who first got to the bottom of the matter. Their law of inertia states that everybody remains in a state of rest or uniform motion if it is not forced to change its state by forces acting on it. In other words: no force is needed to *maintain* motion. Forces *change* movements.

This contradicts our everyday experience that when we throw an object it will eventually come to rest, as if of its own accord. But Galileo had recognised that bodies flying through the air or rolling on the ground are subject to frictional forces that slow them down. Without them, the stone would fly on for all eternity.

Thanks to Galileo and Newton, the term force was clearly defined. Using the laws of mechanical motion that they formulated, we can calculate the parabolic trajectory of the stone using simple formulae: it is the result of various forces acting on it. The idea of impetus and the idea of air pushing the stone during its flight had lost their validity.

> The realization that the parabolic trajectory is a consequence of the interplay of various forces was the result of an intellectual tour de force lasting almost two thousand years.

1.2 The Impulse and the *Ars Viva*

Today the law of inertia in physics is also called the "law of conservation of momentum". So, what is momentum? It is the product of mass and velocity: m times v. In all physical processes, the total momentum of a system is preserved. In the case of a billiard ball that bumps directly into another one, this is easily observed: the masses of the balls remain the same, of course, as do the speeds, but after the impact it is the other ball that moves. This discovery also comes from Galileo and Newton.

However, the momentum of a body does not describe the full extent of its effect in a collision. Two bodies can have the same momentum and yet influence a third body quite differently.

> A body weighing 1 kilogram dropped from a height of 50 centimetres has exactly the same momentum on impact with the ground as a second body weighing 100 grams dropped from 5 metres. Nevertheless, the second body will have a much greater effect. For example, it will leave a correspondingly deeper hole in a soft floor.

The effect of a body on impact depends on the *square* of its speed. Therefore, about 50 years after Galileo, Gottfried Wilhelm Leibniz did not refer to the momentum m v, but to the magnitude $m\ v^2$ as the “true measure” of any movement. For today’s physicists, $m\ v^2$ is a formula for energy. However, Leibniz called $m\ v^2$ the *vis viva*, i.e., “living *force*”. As ingenious as Leibniz’s discovery of the term $m\ v^2$ may have been, the difference between force and energy was still completely unclear to him. And with his *vis viva*, the impetus theory, which had recently been written off, was allowed to sneak back in through the back door.

It took a very long time for physicists to clarify the basic concepts of force, momentum, and energy.

1.3 The Great Energy Confusion

The idea that *force* is a characteristic feature of all living things has a long philosophical tradition. Even the ancient philosophers of nature spoke of forces giving life to things. Aristotle thought up the word “Energeia” for this. He derived it from the Greek word “ergon”, which means “work” or “deed.” “Energeia” thus gives an object the property of being in motion or causing it to move.

So Aristotle said "energy" and meant "force", in modern terms. Leibniz said "force" and meant "energy". What a mess! But modern science needs unambiguous terms to function effectively. It took another century after Leibniz before clarity was finally achieved.

The confusion was not yet noticeable, because Leibniz's contemporaries and others later in the eighteenth century were hardly interested in his *vis viva*. For them it was more a philosophical speculation than a matter for natural scientists. It was not until the early nineteenth century that the physicists Thomas Young and Gaspard Gustave de Coriolis dared to formulate the first concept of energy:

> Energy is the ability of a body to cover a certain distance against a resisting force.

The simplified formula is: **Energy equals force times distance**. To be mathematically exact, however, one must form an integral: $E = \int F \cdot ds$. In mechanics, energy has another name: work. So work is the mechanical energy that you have to expend to carry stones up a mountain, for example.

However, it took several decades before the concept of energy gained a foothold in the sciences and was really understood by physicists. This process was given a major boost by the triumphant advance of steam engines from the nineteenth century onwards. In order to build ever better machines, people wanted to understand exactly how they worked.

Forces move things and bring about concrete changes. Energy describes the *ability* to exert a force.

1.4 Steam Engines as a Driver for Basic Research

In a steam engine, heat is the driving force for mechanical work. Water is transformed into the gaseous state by heating. With part of its energy the steam drives a piston, cools down again and condenses back to water. During the next heating phase, the whole process starts all over again.

Physicists began to understand that the amount of heat lost by the water vapour to the piston is related to the mechanical energy that drives the piston.

The English physicist James Prescott Joule finally showed with a clever experiment that heat and energy are *directly* related. He made a paddle wheel rotate in a container of water and measured its temperature. Over time, the temperature slowly rose. Joule found that a certain amount of mechanical work corresponded to a certain temperature change. Joule also studied other forms of energy, such as electrical and magnetic energy, and determined how much heat could be extracted from each of them. Here, too, the amount of heat produced was related to the amount of energy introduced.

Now it was no longer such a big step to realise that all forms of energy can be transformed into each other (a list of all seven different forms of energy is given in Annex 1). Thermal energy can be converted into mechanical energy—for example, in a steam engine. It also works the other way round: if you rub your hands on a cold winter's day, you generate heat through mechanical energy.

In 1842 the Heidelberg physician Julius Robert Mayer published one of the most important theorems of physics:

> My assertion is: Falling force, movement, heat, light, electricity and chemical difference of the ponderables are one and the same object in different manifestations.[1]

This statement opened the door to a statement about energy conservation: the total energy of a system always remains the same. Today this theorem is called the **First Law of Thermodynamics**.

Energy can never disappear or emerge from nothing. It is only ever transformed from one form to another.

1.5 The Limits of Energy Conversion

For centuries, researchers and inventors had been trying to build a machine that could perform continuous work without the need for energy. With the law of energy conservation, it became clear that the search for such a *perpetuum mobile* can never be successful, because if a machine consumes energy through its performance, new energy must be supplied to it to

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[1] Mayer (1842).

keep it running. Hermann von Helmholtz formulated this in 1847: "A perpetuum mobile is impossible." He called the reason for this the "principle of conservation of force." Oh dear! Energy and force were still being confused.

In the middle of the nineteenth century, physicists discovered another special feature of energy: energy conversions are only possible under certain conditions. For the heat of a body to be converted into mechanical energy, its temperature must be higher than that of its surroundings. But why is this so? The law of conservation of energy does not prohibit a cold body from becoming even colder in order to transfer energy to a warmer body. But this had never been observed. So there had to be a second fundamental law of heat which limited the applicability of the first law accordingly.

A first important step towards revealing the secret had already taken by the Frenchman Nicolas Léonard Sadi Carnot in 1824. Carnot was not a physicist, but an engineer who wanted to build steam engines that were as efficient as possible. He initially thought that all the thermal energy generated during combustion could be converted into mechanical energy. However, he soon discovered that the maximum yield of mechanical energy depends on the difference between the temperature of the gas in the combustion chamber, where the water is heated, and the temperature in the condenser, where it cools down again.

Unfortunately, Carnot never had a chance to interpret his observations conclusively, because he died at the age of 36 during a cholera epidemic. His work was completed by the German physicist Rudolf Clausius and the Irish physicist William Thomson (later Lord Kelvin). Like Carnot, Clausius and Thomson suspected that there must be a law behind the one-sidedness of heat transfer. This **second law of thermodynamics** was first formulated by Clausius in 1850:

> There is no change of state whose only result is the transfer of heat from a lower temperature body to a higher temperature body.

When Clausius expressed this law in a mathematical formula in 1865, he introduced a new quantity into physics: entropy. This somewhat artificial word means "potential for change". Energy conversion only functions until the heat-transferring body has cooled down to its ambient temperature. Once the two systems have the same temperature, the heat transfer is complete. It is therefore not possible to build a locomotive that sets itself in motion by extracting further heat energy from an equally warm or colder environment.

With the term entropy, physicists had found a very useful description of thermal phenomena. They were now finally able to describe and calculate the theoretical principles of steam and internal combustion engines. It became clear that every heat engine can only convert a certain amount of energy from one form to another, the rest being lost to the environment in the form of waste heat. Moreover, the conversion of all other forms of energy obeys the law of entropy and an efficiency of 100% is never reached. Efficiencies of energy conversion processes will be discussed in the following chapters of this book.

In the late nineteenth century, when physicists were able to look at the atomic level, they realised that entropy could also be seen as a measure of the order of a system. If the particles move quickly and wildly in heat (in solid bodies the individual particles oscillate strongly back and forth in their solid structure), disorder and entropy are high. If, on the other hand, the temperature is low, the particles of a gas or liquid move only slowly, whereas in a solid body they hardly oscillate at all. Barely any energy can be extracted from such small movements—the entropy of the system is low.

The second law of thermodynamics (the entropy theorem) limits the efficiency of heat machines and also of all other energy conversions.

1.6 Maximum Energy in the Smallest Space

Albert Einstein's theory of relativity produced a surprising further aspect of energy. His famous formula $E = mc^2$ places energy in a direct relationship to matter. Mass is thus just another form of energy, namely energy of very high density. The conversion factor, the square of the speed of light, has the very high value of 300,000,000 m per second squared. A single grain of sand weighing 1 mg contains the enormous amount of energy of approx. 100 billion joules, i.e. approx. 28 MWh or 25 tonnes of TNT.

When Einstein established his formula in 1905, he did not yet know how his theory would manifest itself in practice. Where were the enormous amounts of energy that his formula predicted? It was not until 1938 that it was realised that they were lying dormant in the atomic nuclei. The German physicists Otto Hahn and Lise Meitner split uranium nuclei by bombarding them with neutrons. The fission products had slightly less mass in total than the starting material. The missing mass was directly converted into kinetic energy of the fission products. The amount of energy was millions of times greater than that released by conventional chemical reactions. Physicists called this form of energy "nuclear energy".

Hahn and Meitner also showed that nuclear fission energy can be obtained particularly easily from uranium and plutonium nuclei. The genie was now out of the bottle. Less than seven years after the first experimental nuclear fission by Otto Hahn and Lise Meitner in Berlin, the American fighter plane *Enola Gay* dropped the first uranium nuclear bomb in history on the Japanese city of Hiroshima. Three days later, a plutonium nuclear bomb landed on Nagasaki.

The new branch of physics, nuclear physics, was soon able to answer a question that astronomers had been thinking about for an very long time: Where does the enormous luminosity of the sun come from? The origin of solar energy had to be the newly discovered nuclear energy. But physicists already knew that the main components of the sun are not heavy atoms like uranium or plutonium, but light ones like hydrogen and helium. The Russian American physicist George Gamow suspected that the sun's energy source was the *fusion of* hydrogen nuclei to form helium nuclei. Physicists call this process "nuclear fusion". The calculations showed that the fusion process of atoms must release even more energy than fission.

On 31 October 1952 the first hydrogen bomb was detonated by the USA. It had 800 times the explosive power of the Hiroshima bomb. On 12 August 1953 the Soviet Union followed suit. Eight years later, they detonated the most powerful nuclear weapon ever exploded with 57 megatons of TNT equivalent—it had the explosive power of 57 million tonnes of TNT. Nuclear energy had enabled humans to destroy their own species.

The formula $E = mc^2$ tells us that matter is nothing but "condensed energy". Its first technological application was the atomic bomb.

1.7 Energy and Life

Julius Robert Mayer, who was the first to recognise the law of conservation of energy in 1842, had come up with this crucial idea on a trip to East Asia. As a ship's doctor, he had bled sailors and observed that their venous blood seemed lighter and therefore richer in oxygen in the tropics than in cooler regions. He saw the reason for this in the fact that the human body needs less heat in these regions, so it has to burn less and correspondingly less oxygen is withdrawn from the blood. Mayer was thus also the first person to identify the chemical process, now known as respiration or oxidation, as the primary energy source for living beings.

However, his article on the conversion and conservation of energy and its importance for every living being was rejected by the physical journals. Eventually, he published his energy theory in the “Annals of Chemistry and Pharmacy”. Their editor Justus Liebig had a better understanding of Mayer’s ideas, as he had stated shortly before in his own article that living beings need food to cover their energy needs. This is how one of the most important findings in the history of physics first appeared in a journal for pharmacists.

Three years later Mayer published the essay “Die organische Bewegung in Zusammenhang dem Stoffwechsel” (Organic movement in connection with metabolism). In it he presented, among other things, the conversion factor between mechanical energy and thermal energy. This so-called “heat equivalent” is about 4.18. This means that one calorie of heat energy (the energy needed to heat 1 g of water by 1 °C) corresponds to 4.18 Nm (joule) of mechanical energy. In modern physics, the heat equivalent has lost its meaning because calories are no longer considered a unit of energy. Since the introduction of the SI unit system, all forms of energy have been measured in joules.

Mayer’s results corresponded to those of James Joules. A dispute broke out between the two about the authorship of the law of conservation of energy, which caused Mayer to break down psychologically. Julius Robert Mayer is almost forgotten today. He had anchored the concept of energy in biology on several occasions, for he was also the first to mention the possibility that plants could convert light into chemical energy.

From the middle of the nineteenth century, biologists and physicians made further significant progress in understanding life. They realised that Leibniz was not so wrong with his *vis viva.* For energy is directly related to life. No matter whether we walk, sit, lie, or think, our body constantly needs energy. Even when we sleep, our body cells continue to work without a break. The energy required for this comes from outside, through food intake, in the form of carbohydrates, proteins, and other necessary energy sources. Our body can therefore also be seen as an extremely complicated energy conversion machine.

Energy and energy conversion are basic requirements for all life on earth. Thanks to Julius Robert Mayer, the clarification of the concept of energy in physics and the recognition of its significance for biology took place almost simultaneously.

1.8 How We Measure Energy

The long and somewhat convoluted history of the discovery of energy is reflected in the many different units with which it is measured. The standard physical unit of energy today is the joule (or watt second Ws).

> 1 joule is the work required to move a body 1 meter against a force of 1 newton. This corresponds to the energy needed to lift a bar of chocolate one metre.

1 Ws or 1 J is a rather small amount of energy compared to typical energy figures—just a single piece of chocolate supplies our body with almost 100,000 J of chemical energy. Therefore, in practice, kilojoules (kJ) or kilowatt hours (kWh) are usually used for calculations. 1 kWh is 3,600,000 Ws (or joules).

In the older literature a multitude of other units can be found, some of which are still used today to describe energy quantities:

- cal—calorie. According to a definition from 1850, 1 cal is the energy that heats 1 g of water by 1 degree Celsius. This corresponds to a thermal energy of 4.18 J. 1 kcal (kcal, 1000 cal) corresponds to 1.162 kWh.
- Coal equivalent. 1 coal equivalent is the amount of energy released when 1 kg of hard coal is burned. It corresponds to 8.141 kWh or 7000 kcal. The value is usually calculated in millions of tonnes of coal equivalent.
- BTU—British Thermal Unit. One BTU is the thermal energy required to heat 1 British pound of water by one degree Fahrenheit. 1000 BTU corresponds to 0.293 kWh. When BTU is used, the thermal energy is usually referred to in "billion BTU".
- OE—*oil equivalent*. An OE is the amount of energy released when one kilogram of oil is burnt. 1 OE corresponds to 11.63 kWh. In world energy statistics, we encounter values in millions of tonnes of OE, i.e. megatons OE (Mtoe).

Now a word about **power**. It is measured in watts. If you leave an old light bulb with the power of 60 W on for 1 h, it uses an energy of 60 W h, i.e. 0.06 kWh.

> Power is the energy expended divided by time. If 1 joule of work is done in 1 second - that's approximately how long it takes to pick up a bar of chocolate - this corresponds to a power of 1 W.

An older unit used to describe power is horsepower. This term, which originated from James Watt himself, was intended to represent the average work output of a horse. But in the end, it was not horsepower but the name of the engineer and inventor that became established as the unit for power. By the way, James Watt had set the horsepower surprisingly high: 1 horsepower equals 746 W. Normal trained people can manage 200–250 W on an ergometer for a certain time. Horses can only achieve 1 horsepower when sprinting, and even eighteenth century plough horses could hardly have maintained this power for more than one furrow of land.

The official measure for all types of energy is the joule (J), but sometimes the kilowatt-hour (kWh) is also used.

1.9 Energy on a Global Scale

Like every living being, our planet with its lakes, oceans, deserts, forests, clouds, cities, animals, people, and plants is a system that constantly converts different forms of energies into each other. The source of almost all energy here on earth is solar radiation, which hits the earth with an average output of 1367 W/m^2. This value, also known as the "solar constant", is an average value because the distance between the earth and the sun varies between 147 and 152 million kilometres over the course of a year. Accordingly, the irradiance varies between 1325 and 1420 W/m^2.

In total, the sun supplies the earth's surface with energy of 1.5 10^{18} kWh per year. It warms the earth's surface and atmosphere, causes water to evaporate, and drives clouds, wind, and ocean currents. Last but not least, this amount of energy is the basis for all life on earth: plants convert sunlight through photosynthesis into chemically high-energy carbohydrates. These fuel the entire food cycle in which humans are also involved.

Only a few energy sources cannot be attributed to solar radiation. These are the exceptions:

- Geothermal energy, which comes from the hot core of the earth,
- Tidal energy, which is the result of the interaction of water with the gravity of the earth, moon, and sun,
- Nuclear energy, which is produced either by fusion or by the fission of atomic nuclei.

Solar energy is the energetic basis for our biosphere. Almost all the energy available on earth was originally radiant energy from the sun.

Scholars and physicists have long wrestled with the nature of energy. Today we know its various manifestations well and are therefore able to transfer it from one form to another according to our needs. So, have we answered all the questions and reached the end of the path that led from Aristotle to nuclear fusion?

No, because today's physics still has a hard time with the question of what energy ultimately is. What is its essence? We can calculate energies and describe their transformations, but we have not yet understood them. This is what Richard Feynman, probably the most important physicist of the second half of the twentieth century, wrote in his famous "Feynman Lectures":

> It is important to realise that in today's physics we have no knowledge of what energy is.[2]

Annex 1: Energy in Various Guises

1. **Kinetic energy**

This form of energy relates to movement. For thousands of years, wind and water mills have used the kinetic energy of flowing air (wind) and water. Often our aim is to convert other forms of energy into kinetic energy. In petrol and diesel cars, the chemical energy of the fuel is converted by combustion, first into thermal energy and then into the kinetic energy of the vehicle. In electric cars, it is electrical energy that enables them to move.

2. **Potential (positional) energy**

An object at rest, which is higher in comparison to another local level, has a corresponding positional energy. If the object is dropped, this energy can be converted into kinetic energy. In storage reservoirs, energy is stored in the form of potential energy. If necessary, the water is drained to a lower level and

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[2] Feynman (1965).