Background for stories concerning energy

From the educational point of view, there appear to be three aspects which are relevant with respect to teaching energy in lower secondary school: Energy as a concept, together with energy conservation, renewable energy, and energy efficiency. The aim of this historical background is to form a basis for stories that may be used individually or combined, and that enable teachers to address these three aspects.

The historian and philosopher of science Thomas Kuhn pointed out that up to twelve researchers can be identified as being involved in the establishment of the principle of energy conservation (Kuhn 1959). One of those researchers, James Prescott Joule, can be seen as a central figure to this background. Joule is a central figure as he is the person who established the mechanical equivalent of heat – at least this is the standard notion. However, if one takes a closer look, then it gets evident that it was not just Joule who is responsible for establishing his work, but also William Thomson, who later became Lord Kelvin. Yet, search on using solar energy for industrial machinery.

Count Rumford and his work on heat

Rumford's work on heat covers a huge variety of researches; he worked significantly on the topic for some 25 years. His first research in this respect resulted from his military context: he examined the quality of powder (Thompson 1781). In doing so, he suspended the cannon as well as a ballistic pendulum, the amplitude of the oscillation after firing the powder served as an indication of its quality.

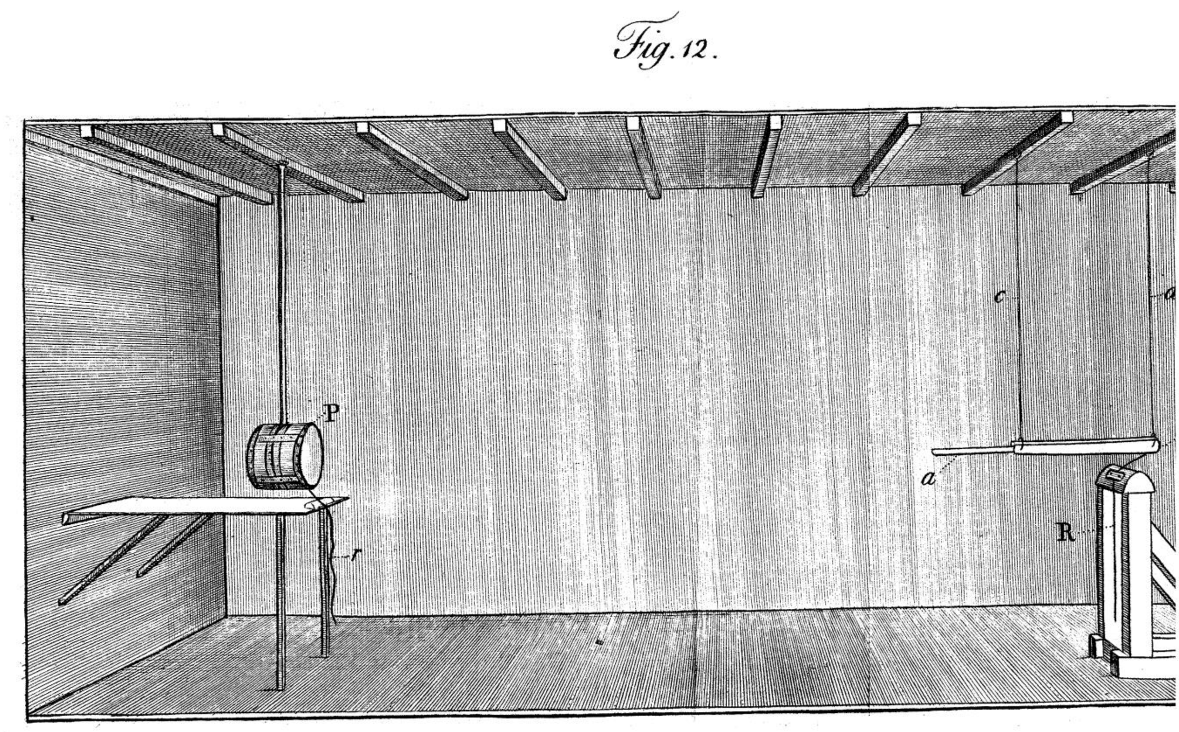

Fig. 1: Rumford's experiment on the quality of gun-powder. (Thompson 1781)

Joule himself did not start from scratch and particularly referred to the work of Benjamin Thompson, Count Rumford, who carried out researches about heat in late 18th/ early 19th century. Actually these researchers were more oriented on practical purposes than those of Joule. The first significant aim towards renewable energies can be seen in the work of the French teacher Augustin Mouchot who, in the 1870ies carried out substantial re-

Whilst the initial research in not that important with respect to energy, one detail actually is: Rumford observed that the cannon heated up most when he did not shoot a bullet but just made the gunpowder explode in the barrel. When being in Munich and having the responsibility for the production of weaponry, Rumford made another observation that he turned into an experiment: In the process of cannon-boring, the metal heated up. Rumford used a blunt drill in order to increase the

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heat production. In doing so, he was able to heat up the water (and that was a mass of 26.58 lb) that was initially intended for cooling to the boiling point (Thompson 1798).
At the same time, Rumford demonstrated that the heat capacity of the metallic chips that were produced in the process of drilling was not changed in their heat capacity. From his experiments, Rumford concluded that heat can be produced from mechanical work in an unlimited amount – as the production of material substances was not in accordance with the accepted understanding, he had also to conclude that heat is not a substance but the motion of the smallest particles of matter.

Doing so brought him in conflict with the most recent accepted doctrine with respect to heat: In 1789 the French chemist Antoine Laurent Lavoisier published his famous Traité Élémentaire de Chimie … (Lavoisier 1789). In this monograph as well as in a variety of research papers Lavoisier used the term caloric. For Lavoisier, caloric was one of the "simple substances belonging to all the kingdoms of nature, which may be considered as the elements of bodies" (Lavoisier 1790, p. 175). This substance was said to be weightless and thus considered to be one of the imponderables. Other imponderables were the matter of light (in Lavoisier's nomenclature lumic), moreover, there were one or two electric and magnetic fluids. Caloric was taken to be the explanation for the phenomena connected with heat. In some attributes caloric was very similar to the older substance named phlogiston, although there were important differences between Lavoisier's System and the one founded by Becher and Stahl. This played also a role in naming the first instrument that enabled measurements of the amount of heat calorimeter (Roberts 1991, see also Beretta 2005), the ice calorimeter.

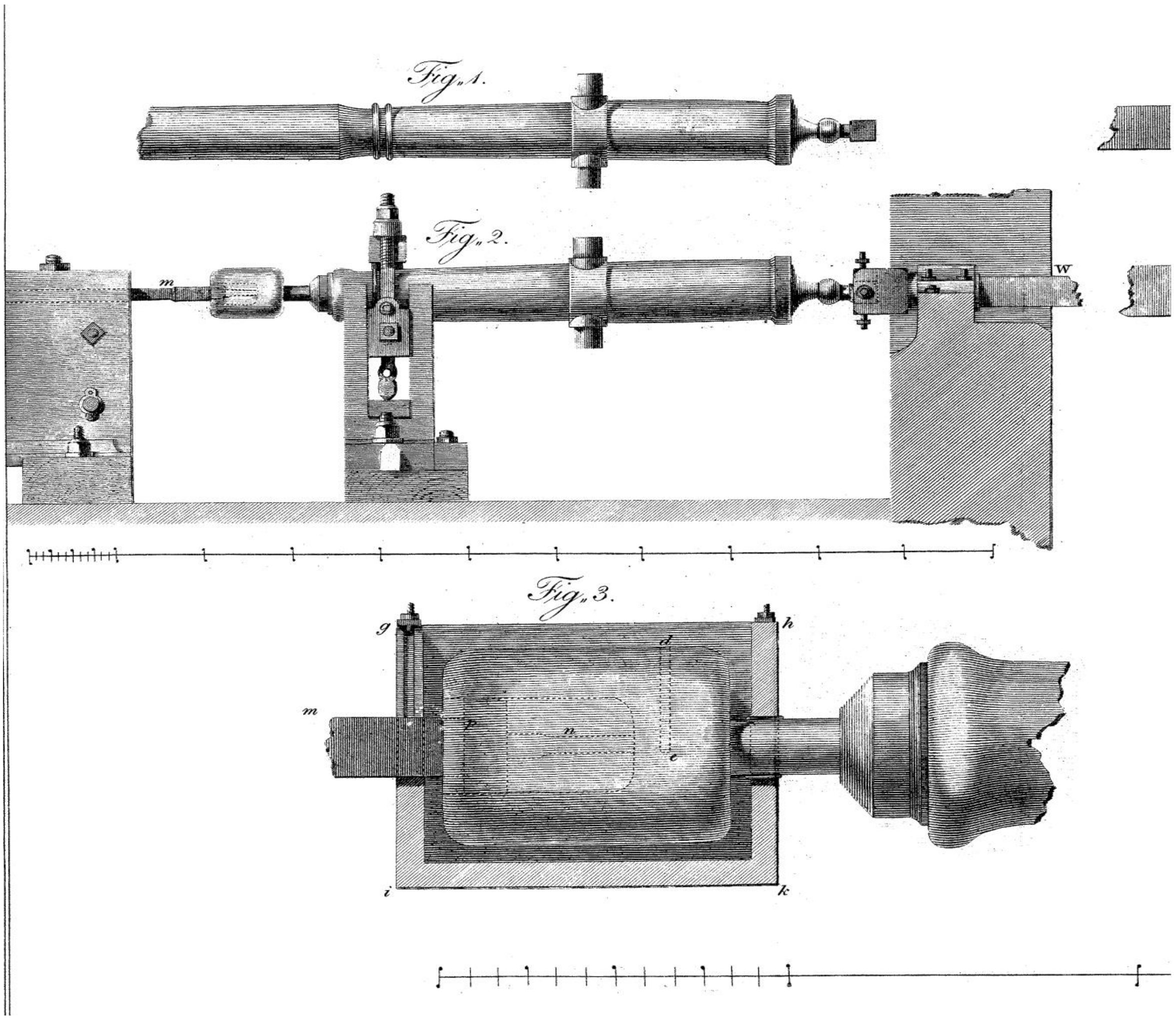

Fig. 2 Rumford's cannon-boring experiment (Thompson 1798).

For the discussion of Rumford's work with respect to energy conservation, the importance of Lavoisier's work lies not in the fact that his system can be seen as the accepted theory – and actually Rumford's work did not change this impression significantly, on the very contrary: In the first quarter of the 19th century, heat was a material substance and most researchers identified this substance with Lavoisier's caloric. The im-

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portance for Rumford's work lies in the postulated indestructibility of the elements. As caloric was one of Lavoisier's elements (even though imponderable, but it was listed in his system as an element such as Oxygen or Iron), it was obvious that this substance could neither be destroyed nor created. Thus the idea of conservation was established in the theory of heat.

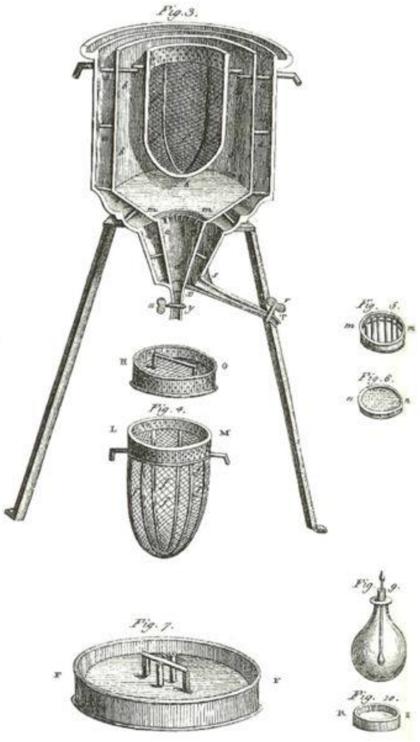

Fig. 3:Ice calorimeter by Lavoisier and Laplace (Lavoisier 1789), https://upload.wikimedia.org/wikipedia/commons/3/35/Ice-calorimeter.jpg

Whilst Rumford's cannon boring experiments can be seen in direct relation to the establishment of the theory of heat, two other of his research projects appear to be relevant in the context of the project too: On the one hand, he analyzed the radiant heat. This became a topic in natural philosophy at the very beginning of the 19th century when William Herschel (who is besides this work best known for his discovery of Uranus) came in a series of measurements to the conclusion that the radiation from the sun did not just consist of light, but also contained radiant heat which had its largest intensity beyond the red part of the spectrum.[1]

These 'new rays' became an issue of investigation for several researchers, most namely John Leslie who published in 1804 a monograph dealing with this issue. However, Rumford published also in 1804 an investigation in which he analyzed the ability of various materials to emit radiant heat.[2] Whilst this inquiry may be seen as fundamental research, there are also aspects of applicability in his investigation: it was relevant with respect to the improvement of the efficiency of stoves, an issue that had been central to Rumford's work for decades.

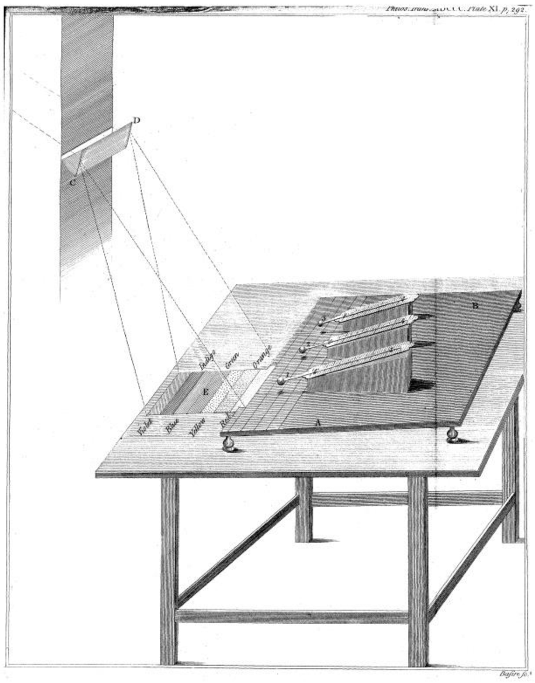

Fig. 4: Herschel's experimental set-up for the discovery of radiant heat, Herschel 1800.

Rumford developed an instrument that he called thermoscope. This instrument consists of a glass capillary that is U-shaped. At both ends of the capillary, hollow spheres are attached. These spheres are blackened and made from very thin glass. Due to the blackening, the glass spheres absorb radiant heat, as the glass is very thin, the absorbed heat is conducted to the air inside of the sphere. As the capillary is closed, due to the increase of temperature, the pressure is increased as

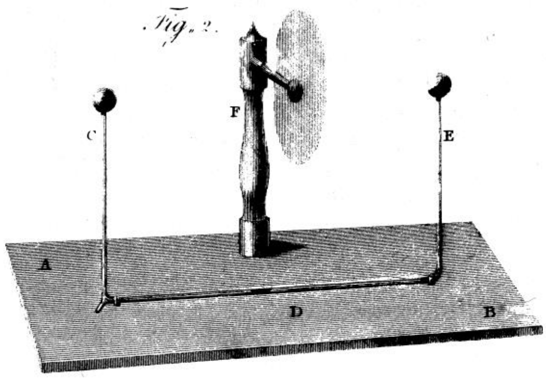

Fig. 5: Rumford's thermoscope, Thompson 1804

[1] The background of these experiments was the idea to find out which part of the (visible) spectrum might affect lenses in a telescope in the most significant manner due to heating up the glass.

[2] See Leslie (1804) and Thompson (1804), for a discussion of these investigations see Olson (1970).

well, consequently, the pressure on each side is related to the absorbed radiant heat.

In the middle of the horizontal part of the glass capillary, a drop of alcohol is placed. When the pressure in both arms is different, the drop moves towards the side of lower pressure. Consequently, the gas at lower pressure is compressed whilst the gas at higher pressure expands until pressure equal pressures are reached. Between the two spheres, a copper disc is placed, thus the heat emitted from a source that is placed in a geometrical line with the two balls can affect only one of the spheres.

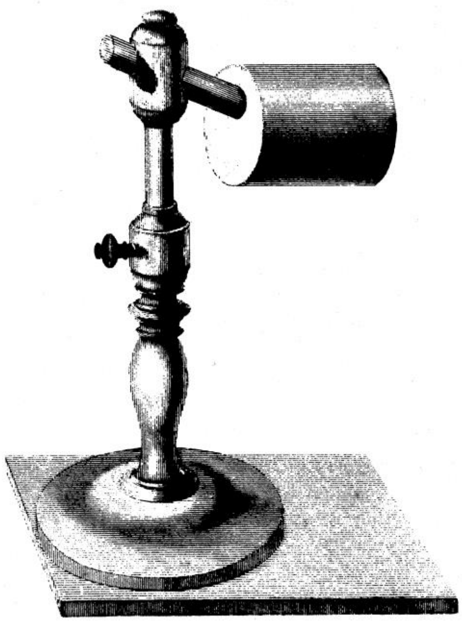

Fig. 6: Rumford's heat radiator, Thompson 1804.

The thermoscope is placed on a wooden frame. On both sides, heat sources (metal cans filled with hot water) can be placed and changed in their distance towards the thermoscope. At the beginning of each experiment, both heat sources are placed in the same distance. Due to the absorption of radiant heat and the resulting different pressure, the alcohol drop starts to move. The experimenter increases the distance between the stronger heat source and the thermoscope until the alcohol drop is in its initial equilibrium position. Comparing the distances of the two sources to the thermoscope serves as an indicator of their emission – Rumford took it for granted that the heat emitted from decreases with the inverse square of the distance. This relation was already demonstrated by the Swiss mathematician Johann Heinrich Lambert for the decrease of light intensity with the distance, a work Rumford was through his own work in the field of photometry familiar with. Lambert's relation s appeared to be plausible for radiant heat as well – on the one hand due to its similarity with light, on the other as an isotropic radiation decreases with the inverse square of the distance.

Yet, the question of improving the efficiency was not limited to his work on radiant heat and stoves. Another research that can be seen in this context was his analysis of the insulating properties of different materials. This analysis was also carried out whilst Rumford was minister of war in Munich, and was in a broader sense related to a military issue. The aim was to develop the basis for determining the most suitable material for the uniforms of the Bavarian soldiers who ideally would get only one type of uniform that was supposed to be suitable for winter as well as summer. Like in the experiment on analyzing radiant heat, Rumford used metal cans as heat sources. These cans were covered with different clothing materials, hot water was filled in, and Rumford observed the decrease of the waters temperature. In doing so, he was able to determine the most efficient way to insulate the human body.

To summarize, Rumford can in retrospect be identified as a starting point for various development in the energy science – he carried out experiments that were related to the formulation of the principle of energy conservation as well as to a field that nowadays can be labeled 'energy efficiency', particularly with respect to different materials.

The formulation of the principle of energy conservation

Joule started his research in analyzing electrical motors.[3] This was directly related to his work in the brewery his father owned. Here, steam engines were used, and, after the development of the electrical motor, the potential of this new device seemed to be superior to the one of a steam engine. Consequently, Joule's aim seemed to have been the construction of an economical electromagnetic engine. This can be derived by the following: "I can hardly doubt that electromagnetism will ultimately be substituted for steam to propel machinery. ... the economy (of an engine) will be in direct ratio of the quantity of electricity, and the costs of working the engine may be reduced ad infinitum" (Joule 1884, p. 14). This idea of an 'economical perpetuum mobile' is not just found in Joule's writings, but many scholars of this time held this opinion.[4] Joule finally came

[3] On the early history of electrical motors see in particular Schiffer (2008).

[4] This is not to be confused with a scientific perpetuum mobile as it has been done e.g. by Breger: "Obviously Joule has no principal objection to a perpetuum mobile at this time;

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to the conclusion (like other scholars) that the zinc that reacts in the galvanic element is more expensive than the fuel for a steam engine which is supposed to carry out the same work like the electrical motor.

During the following years, the subject of Joule's research was the production heat either by voltaic electricity, in batteries or in chemical combustion; these investigations were quantitative. After completing this research, Joule turned to a new topic: in 1843, on the occasion of the meeting of the British Association for the Advancement of Science, Joule presented a paper° which initiated his later prestige. He described the new subject of his investigations in announcing that "having proved that heat is generated by the magneto-electrical machine, and that by means of the inductive power of magnetism we can diminish or increase at pleasure the heat due to chemical changes, it became an object of great interest to inquire whether a constant ratio existed between it and the rnechanical power gained or lost" (Joule 1884, p. 149). Joule performed new experiments to demonstrate the existence of a mechanical equivalent of heat and to determine its numerical value. From a first series of experiments he determined the coefficient as 838 ftlb/BTU, in a second series published in the same article he gave 770 ftlb/BTU.

Looking at the data Joule published gives some insight into Joule's theoretical background. The equivalents he calculated with the data in his paper were (in ftlb/BTU): 896; 1001; 1040; 910; **1026; 587**; 742 (mean of five experiments); 860 (mean of two experiments); 770. The two bold data derive from experiments "conducted in precisely the same manner" (Joule 1884, p. 153). It seems to be daring to take these data as a proof for the existence of any equivalent, in other words, Joule had to believe in the existence of a mechanical equivalent of heat in order to formulate this result from his data. The data could also be interpreted as an indication that the amount of heat produced from the same mechanical work may differ significantly, depending on some unknown or at least unclear parameter. However, Joule came to the formulation that there is a mechanical equivalent of heat, and that the deviation of the data are caused by the reading limitations in his experiments: "I admit that there is a considerable difference between some of the results, but not, I think, greater than may be referred with propriety to mere errors of experiment" (Joule 1884, p. 156).

Although Joule realized the difference between his data, he claimed to have proved the existence of a mechanical equivalent of heat. Therefore, it seems to be plausible that he came not to believe in the existence of the equivalent from his experimental data but for other reasons. Towards the end of his research on this topic, Joule himself gave an insight into these reasons declaring that he was "satisfied that the great agents of nature are, by the Creator's fiat, indestructible; and whatever mechanical force is expended, an exact equivalent of heat is always obtained" (Joule 1884, p. 158). This statement gives an imagination of the theoretical background Joule had in mind when trying to determine the mechanical equivalent of heat. For Joule it was not compatible with his view of nature that anything could be destroyed or created. He had embodied the idea of conservation in a way that made it impossible to accept any exceptions of this principle. But there seemed to be several exceptions as, for example, the generation of heat by the magneto-electrical machine. Therefore, it was necessary for Joule to develop a new idea, the idea of equivalent transformation of what he called great agents of nature. This idea, the equivalent convertibility, is the great conceptual step that was necessary to come from the principle of conservation of heat (as caloric) in Lavoisier's sense to the principle of energy conservation.

The paper Joule presented in 1843 was not paid much attention to in the scientific world. In the following years Joule presented several papers in which he described various different experiments he made to determine the value of the mechanical equivalent of heat with higher precision. Two of these papers are noteworthy for completely different reasons. One was published in the Philosophical Transactions of 1850, it was entitled "On the Mechanical Equivalent of Heat". In this paper Joule described in full detail his experiments with the famous paddle-wheel. This paper did not only include the data Joule got from his experiments and the calculation of the mechanical equivalent, but also a detailed description of the experimental set-up. Additionally, Joule described his experiments on the friction of mercury and of cast iron. In a way, the publication of this paper in the prestigious Philosophical Transactions can be seen as a strong indicator of the acceptance of Joule's work by the British scientific community.

The other important paper Joule presented at the annual Meeting of the British Society. As his biographer D. Cardwell pointed out: "Joule believed his paper would have passed without notice

obviously he thinks that an inexhaustible source of power is practicable"(Breger 1982, p.194).

had not a young man at the back of the hall risen and asked penetrating questions that created a lively interest in the paper" (Cardwell 1989, p. 83). This young man was William Thomson, later Lord Kelvin. He was one of the first really influential scientists, and he was the first interested in Joule's results. Although he did not agree with Joule's ideas at first, he became convinced and not only supported Joule's theory, but also started a successful collaboration with him.

Thomson was skeptic about Joule's experimental claims as he was trained in part in France where he became familiar with the work of Victor Regnault and Sadi Carnot. The latter had demonstrated that the work of a steam engine is depending on the temperature difference, thus the work was not equivalent to a specific amount of heat, but depending on the temperature differences. Only when the concept of energy and energy dissipation (and in this respect entropy) had been developed, both Joule's and Carnot's findings were no longer in contradiction. In some sense, this contradiction together with the growing acceptance of the energy concept triggered the development of the energy concept. Only during the collaboration Thomson became convinced that Joule's results were correct and important, in the following he supported Joule in the scientific community.

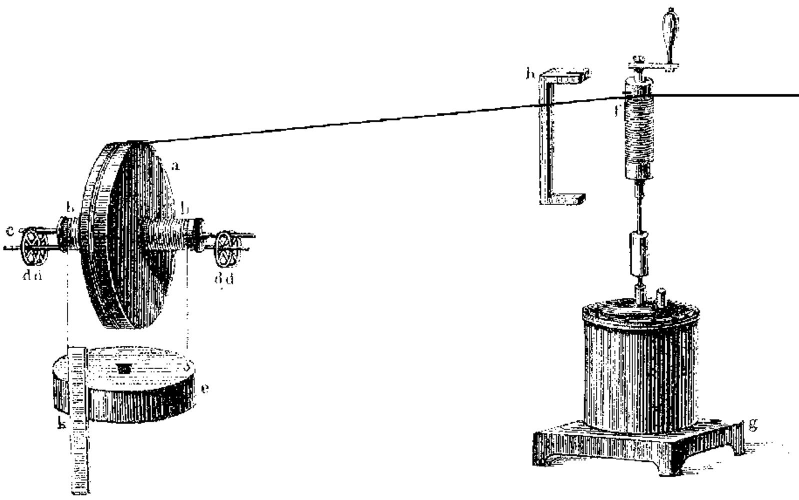
Fig 7: Joule's paddle wheel apparatus, Joule 1872

This aspect is relevant for the acceptance of Joule's work in the British scientific community: Ignoring his findings may in part be explained by the fact that Joule was a brewery owner in Manchester. Even though this turned out to be crucial for Joule's experimental resources (which will be discussed later) it also caused a difficulty: Even though conceptual difficulties played a role, it was also Joule's status that was meaningful. He was not a trained scientist but more a 'gentlemen of science' without a scientific CV or position. Whilst this was the standard during the 18th and in the early 19th century, in the middle of the century the situation had changed. Science became more and more professionalized in Britain, and part of this professionalization was the resulting limitation of science to professional practitioners. There were of course exceptions, most notably Michael Faraday, however, when Joule started publishing on the mechanical equivalent of heat, his social status was certainly an issue. On the other hand, William Thomson was well trained, a young professor at the University of Glasgow and, despite his age, already well-established in the scientific community. Thus, it was not just the individual Thomson who supported Joule's work, but also the scientists with his status. Consequently, the support by Thomson contributed to the acknowledgment of Joule's work.

But it is not a question of social status that is interesting in Joule's work: His experiments are equally remarkable. To give but a brief description on the experiment: Figure 7 is a perspective view of the set-up Joule gave in his paper.

aa are wooden pulleys; l foot in diameter and 2 inches thick, with wooden rollers, bb, bb, 2 inches in diameter, and steel axles, cc, cc, one quarter of an inch in diameter. The pulleys were built perfectly true and equal to one another. The axles were supported by brass friction wheels dddd, dddd, the axles of which worked in holes drilled into brass plates attached to a strong wooden table, which Joule affixed to the wall of his laboratory. The weights e, e, were suspended by string from the rollers bb, bb; and fine twine attached to the pulleys aa connected them with the central roller f, which, by means of a pin, could easily be attached to, or removed from, the axis of the frictional apparatus. This apparatus is represented in figure 8 (left) vertically and in figure 8 (right) horizontally. It consisted of a brass paddle-wheel furnished of 8 sets of 4 revolving arms each and 4 sets of 4 stationary vanes each. The brass axis worked freely and was divided at d into two parts to avoid any conduction of heat in that direction. The paddle wheel firmly fitted into a copper vessel with two holes in the lid, one for the insertion of the axis, and one for the insertion of a thermometer. During the experiment a large wooden screen was attached to the table to avoid all effects of heat radiation from the experimenter.

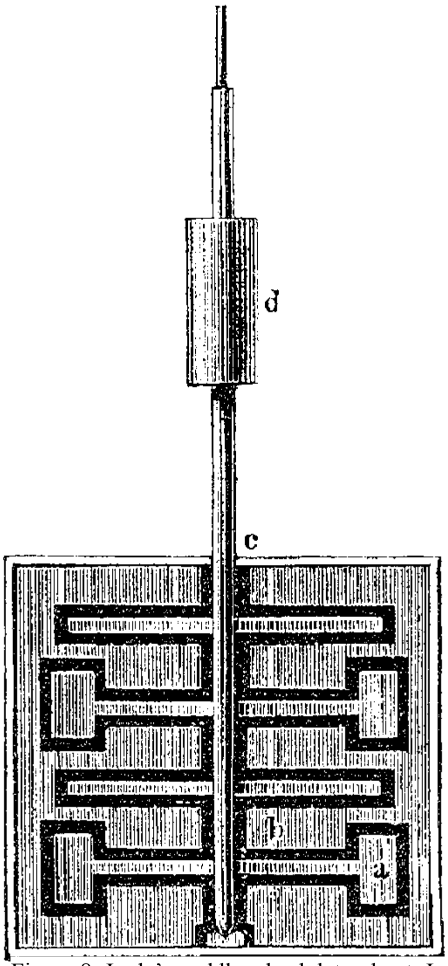

Figure 8: Joule's paddle wheel, lateral cut. Joule 1872

At the beginning of the experiment, the vessel is filled with water, and it needs about 6 l of water to fill this vessel. When everything is in thermal equilibrium, the temperature of the water as well as the one of the room is measured, and the thermometer is removed from the vessel. Then the weights of a total of 26 kg are wound up for about a meter and then go down, driving a paddle-wheel that is stirring the water. This procedure is repeated twenty times, and it takes some 35 minutes to realize these 20 runs. In the end, according to Joule's data, an increase of the water temperature of approximately 0.5°C can be measured.

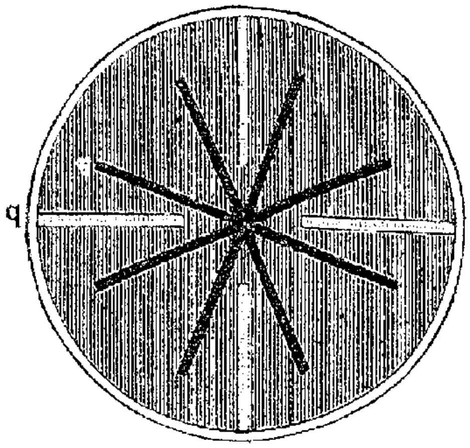

Figure 9: Joule's paddle wheel, horizontal cut. Joule 1872

Analyzing this experiment reveals some details that are noteworthy and which show that Joule was in an extraordinary situation: Joule was able to employ some of the most skilled craftsmen who were at hand in an industrial town such as Manchester. The instrument maker – John Benjamin Dancer – was extremely versed and particularly able to create extremely sensitive thermometers. Their sensitivity was extraordinary: "The two thermometers he (Joule) had acquired in 1844 were, he claimed the first accurately-calibrated thermometers in Britain … ." (Cardwell 1989, p. 234) The thermometer which was used to determine the temperature of the water had a length of 87 cm and had a range from freezing point to about 85°F (see Ashworth 1930). Joule wrote that "constant practice had enabled me to read off with the naked eye to 1/20 of a division it followed that 1/200 of a degree Fahr, was an appreciable temperature" (Joule 1884, p. 303). At such a degree of sensitivity, water is far from being at a constant temperature. Consequently, the procedure of determining this temperature is far from being easy. Instead of waiting until the mercury column of the thermometer comes to rest and then read the temperature, Joule had to find other means to determine when the thermometer and the water were in thermal equilibrium. As Sibum demonstrated, measuring temperatures was part of the brewer's culture, thus Joule had the respective competence to carry out the measurement from his professional background.

There are other aspects which indicate that this experiment was embedded in the brewers' culture: Joule used a copper vessel without any insulation, even though the room should not affect the thermal condition of the water in any way. This may

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seem a bit unusual, particularly when one takes into consideration that Joule actually used a wooden shield to protect the vessel from the radiation of the body of the experimenter. However, the copper vessel is a device commonly used in beer brewing, thus Joule was very versed in controlling the thermal situation in such a vessel – an insulated one (which could not be perfectly insulated) was not familiar as a system to Joule.

But there are also material aspects in the Manchester brewery that enabled Joule to carry out his experiment successfully. On the other hand Joule needed a room with a huge heat capacity – otherwise the heat produced by the human body in winding up the weights would affect the room temperature and thus the experimental result significantly. Such a room exists in a brewery: the cellar in which the beer is stored. This has a huge heat capacity and thus an almost uniform temperature, thus it was a room with the physical properties that were necessary for the production of reliable data. On the other hand, Joule could use a brewing mate to do the work of winding up the weights. This required certain skills as the weight is heavy, and one has to be fast and controlled at the same time to do this work. Joule himself was not in the physical position of doing this work, moreover, he was a gentleman, and doing such a work would not correspond to his social status.[5]

Starting research on renewable energy

In mid-nineteenth century, industrialization progressed at high speed. One of the side effects was the necessity to have fuel for the seam engines that were the central power source in the factories. To France, this started to pose a major problem, as the coal deposits turned out to be limited and were almost exhausted. This was even more a problem as the potential imports could only come from England – the traditional (economic) rival to France. Consequently, the French government promised financial support to any researcher who proposes promising concepts of how to avoid a dependency of France from English coal.

This was the moment when the French secondary school teacher Augustin Mouchot entered the stage. Mouchot combined two devices that had been known previously: A blackened hollow cylinder containing water – a similar device had been used by the end of the eighteenth century by Horace Benedict de Saussure for making experiments on heat radiation. This was combined with a hollow mirror that was used to focus solar radiation on the cylinder. Already in 1861, Mouchot was able to produce steam with his device. In the following years, he intended to improve his set-up to make it more useful for technical purposes. The attempts were financially supported by the French government.

Two outcomes can be named as direct results: On the one hand, Mouchot was able to develop solar cooking devices, items that were used in particular by the French army in their North African colonies. These devices enabled the soldiers to prepare hot meals without producing smoke, a detail relevant from a military perspective. These cookers were used until the 20th century.

The other result of Mouchot's attempts was a steam engine that was operated with steam produced by his solar apparatus. Mouchot devised several of the engines, the largest was shown at the world exhibition in Paris in 1878. The conical mirror had a diameter of some five meters, and the engine could be used as a printing device, but was also able to produce ice.

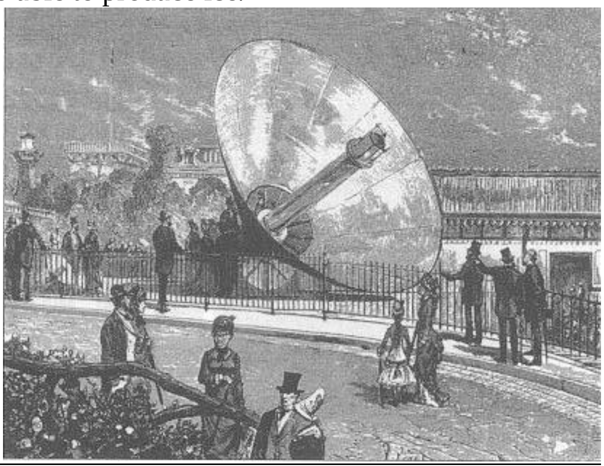

Figure 10: Mouchot's apparatus at the Paris World Fair, http://upload.wikimedia.org/wikipedia/commons/6/66/Mouchot1878x.jpg

Mouchot was awarded a gold medal for this machine. Yet, by this time, things had changed once again. A major problem of Mouchot's machine remained the mirror which was made with a silver coating – this tended to oxidize, thus reducing the efficiency of the machine and requiring a constant cleaning of the mirror. However, another development turned out to be far more problematic for Mouchot: Miners had found new coal deposits in Eastern France, consequently, the necessity for finding an alternative source of energy for the steam engine did not exist any longer. Moreover, in a report Mouchot's machine was labeled as economic inefficient. As a result, the French gov-

[5] Similarly, Joule did not mention the person doing the physical work in the experiments he carried out afterwards which led to what is nowadays known as the Joule-Thomson-Effect (see Sichau 2000).

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ernment ceased to support Mouchot's research financially; this brought his work to an end.

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Background for stories concerning energy was written by Peter Heering with the support the European Commission (project 518094-LLP-1-2011-1-GR-COMENIUS-CMP) and Flensburg University, Germany. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.