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From the water wheel to turbines and hydroelectricity. Technological evolution and revolutions

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ABSTRACT

Since its appearance in the first century BC, the water wheel has developed with increasing pre-industrial activities, and has been at the origin of the industrial revolution for metallurgy, textile mills, and paper mills. Since the nineteenth century, the water wheel has become highly efficient. The reaction turbine appeared by 1825, and continued to undergo technological development. The impulsion turbine appeared for high chutes, by 1880. Other turbines for low-head chutes were further designed. Turbine development was associated, after 1890, with the use of hydropower to generate electricity, both for industrial activities, and for the benefits of cities. A model "one city + one plant" was followed in the twentieth century by more complex and efficient schemes when electrical interconnection developed, together with pumped plants for energy storage.

1. Introduction

The appearance of water power was, for mankind, a major technological revolution. This history starts as early as classical Antiquity. Water technologies for gravity irrigation had been used in the Middle and Far East since the fourth millennium BC, and aqueducts have been developed in the countries around the Aegean Sea, prior to their use in the Roman world. A new climate favorable to water technology innovation appeared from the third century BC, during the Hellenistic period, around knowledge centers as Alexandria (Egypt) and Pergamon (in today's Turkey), with new water lifting devices as the tympanum, the saqqya, the Archimedes screw, the Ctesibios pump [1].

The vertical water wheel was born somewhere in the Middle East during the first century BC, as suggested by the earliest textual mention by Strabo [2] of a water mill in Mithridate's palace in Cabeira (north of present-day Turkey). Water wheels further developed to a large extent in the empires of Rome and of China during the first to third centuries AC. In the Roman world, they were mostly used to grid grains, and sometimes also, in the fourth century, for sawing marble. In the Chinese empire, it is known from textual sources [3] that water wheels were used for many industrial purposes (moving bellows for metallurgy, sawing ...). Roman water wheels used to be vertical wheels (the so-called Vitruvius wheel), with diameters between 1.5 and 3.5 m [4,5]. Mills with multiple water wheels existed, for instance in Barbegal, close to Arles, in the south of France [6]. In the Middle Ages, the water wheel continued to develop, in both western and eastern civilizations, together with the demographic development which lasted until the thirteenth century (and ended with the wars and great plague of

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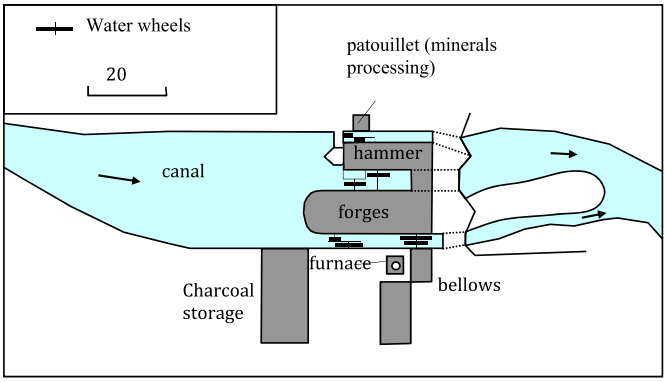

Fig. 1. The Buffon forge in 1828, installed on a canal derived from the Armançon River (France), with eight water wheels.

the fourteenth century). Today's landscape of watermills in the western countryside is mostly inherited from this expansion period.

2. The economic and industrial importance of water power, from the Middle Ages to the nineteenth century

At the end of the Middle Ages and at the eve of the industrial revolution, the water wheel was the support to many economical pre-industrial activities [7–9]: grinding grain, sawing, fulling for textile manufacturing and paper mills, treading cane for sugar processing, moving bellows and water hammers for metallurgy (forges). Water wheels were also used in the mining industry for lifting water from mine pits, fulling minerals, etc. As for Western Europe, the dominant technology was the vertical wheel north of a line between La Rochelle and Lyon and the horizontal water wheel south of this line. Mills on boats anchored on rivers or suspended from bridges, and tidal mills also developed in the same period.

Monks (especially Benedictines and Cistercians) were among the most active communities in the development of watermills, because they had the capacity to develop technological skills, together with available manpower. It is known for example than 84 waterwheels were owned by the abbey of Saint-Germain-des-Prés in France, one of the major abbeys owning lands between the Loire and the Rhine Rivers, by the ninth century [10]. In 1086, after the Norman conquest of England, the Domesday Book identified no less than 5624 water mills in this country.

During the period between the seventeenth and the nineteenth century, there was a progressive development or larger and larger industrial sites using water power as the source of energy [8,11]. Water power was at the origin of the early industrial revolution, the use of coal as a source of energy developed only as a second phase.

Forges using water powered hammers and bellows were installed on multiple canals derived from rivers, with many water wheels powering the different workshops of the chain between raw materials to terminated steel products. It is known from a survey ordered by a minister of King Louis XV that about 140 such integrated forges were in operation in France in 1772 [12]. Fig. 1 shows the example of one of those integrated forges, which was built by 1770 by Buffon, the naturalist and scientist.

The mechanical machine for cotton clothing manufacturing, the *spinning jenny* was invented in England in 1767. It was water powered after 1769, and after that time water powered mills quickly developed in England, in France and slightly later in the USA. While in England the use of coal replaced hydropower after 1830 for cotton manufactures, water power remained the main source of energy for cotton spinning mills in France and the USA. In this country, in New England and Massachusetts, very large mills were built upon canals, which were powered by a large number of water wheels, further to be replaced by hydraulic turbines. In 1823, a group of persons called the *Boston Associates* decided to concentrate upon the site of Lowell, where an existing navigation canal, called the Pawtucket canal and by-passing the falls of the Merrimack River already existed. From 1823 to 1847, ten textile mills were built on this site, as shown in Fig. 2, using 191 water wheels (11).

Many other textile mills were built in the USA. Labor was hard and dangerous for the girls who were working in these textile mills [13].

Water power was also very important for the mining industry. In Germany, a large number of dams and canals were built between the sixteenth and the eighteenth century, in order to supply power to mines in the area of the Metal and Harz mountains. In the Harz mountains, situated between Hanover and Leipzig, more than 100 earth dams were built in the above-mentioned period, with more than 400 km in total length of canals. Those technologies were further transferred to eastern and northern Europe. There were used also in the new world (for instance in the silver mines of Potosi in Bolivia). Very interesting illustrations of the use of the waterwheels in the mining industry of that time may be found in the book written in 1565 by a German scholar (Agricola), and translated into English in 1950 by former US President Hoover and his wife [14].