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Innovations in windmill technology in Europe, c.1500-1800.

The state of research and future directions of inquiry



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1. Introduction

In general surveys on the history of energy in the Middle Ages and the early modern period, windmills normally only take up a modest place.¹ The most common way of presentation is to mention the appearance of the vertical windmill in Western Europe in the High Middle Ages and briefly discuss its spread in later times, but to play down its contribution to the overall energy supply relative to other sources of power. In a short section on ‘the earlier competitors of the steam-engine’ in the once authoritative *History of Technology* published in the 1950s, R.J. Forbes claimed that ‘the windmill was not a popular prime mover in eighteenth-century England, but it played an important part on the coasts of the North Sea and the Baltic’. Yet, ‘the introduction of the windmill as a prime mover did not proceed smoothly’ even in Holland, he asserted, and it reached ‘the upper limits of its evolution (an energy output of about 50 h.p. at the windshaft) in the eighteenth century, after which it ‘inevitably gave way to the steam-engine’.² Carlo Cipolla remarked that windmills had more power than watermills, ‘but for obvious reasons ... never became as widespread and common as the water-mills’. Fernand Braudel thought that the capacity of both waterwheels and windmills was rather low, but

1 This article is a slightly modified and extended version of a paper presented in April 2002 at the XXXIV Settimana di Studi organized by the Istituto ‘Francesco Datini’ in Prato on ‘Economia ed energia, secc.XIII-XVIII’. I am grateful to an anonymous referee for his valuable comments.

2 R.J. Forbes, ‘Power to 1850’, in: C. Singer *et al.* (eds.), *A history of technology*, dl. IV (Oxford 1958) 156-159.



that the spread of these devices, in an economy where energy was very scarce, nevertheless meant a considerable increase of sources of power and certainly made a significant contribution to the first phase of growth of Europe in the 11th-13th century. Although the energy output of windmills exceeded that of waterwheels (5 – 10 h.p. as compared with 2 – 5 h.p), he stressed, waterwheels played a far more important role than windmills, because they were much more common and water was less unsteady than wind.³ Like Cipolla and Braudel, Paolo Malanima underscored the greater power of windmills as compared with water mills. The introduction of “inanimate machines” in the Middle Ages and their spread in the Early Modern Era was of little relevance in overall quantitative terms, he claimed, but they nevertheless marked the beginnings of an ‘energy revolution’.⁴ Vaclav Smil, by contrast, thought that the capacities of common (wind-powered) post mills and watermills during the Middle Ages were about the same, but that by the early nineteenth century many watermills were four or five times more powerful than even the largest (wind-powered) tower mills.⁵ For Rolf Sieferle, the windmill hardly mattered at all: the use of windpower was ‘auf anspruchlosere Anwendungen beschränkt, vor allem das Abpumpen von Wasser in Poldern oder das Mahlen von Getreide’.⁶

But how much do we really know about the spread and power of windmills in the early modern period? Were the uses of windmills indeed more limited than those of waterwheels? And did the technical development of windmills truly fall behind that of waterwheels before the nineteenth century, as Smil insists, or, alternatively, did the windmill reach the upper limits of its evolution in the eighteenth century, as Forbes mistakenly claimed? The answer to the first question, as I will argue in section 1 of this article, is: very little. The knowledge on the spread and energy output of windmills is much more precarious than confident statements on this subject seem to suggest. Section 2 will demonstrate that the uses of windmills during the early modern period became as varied as those of waterwheels and that the growth of new applications did not remain restricted to the heartland of innovation in windmill technology, Holland. Innovation in windmill technology was in fact a much more continuous process than is commonly assumed, I will show in section 3. Windmills had by no means reached the upper limits of their evolution when they almost disappeared from the scene of energy sources after 1900. In line with these findings, the conclusion will suggest some ways for further research.

3 C.M. Cipolla, *The economic history of world population* (Harmondsworth 1962/1974) 51-53, F. Braudel, *Civilisation matérielle, économie et capitalisme*, dl. I (Paris 1979) 308.

4 P. Malanima, *Energia e crescita nell'Europa preindustriale* (Rome 1996) 106-111.

5 V. Smil, *Energy in world history* (Boulder 1994) 108-112.

6 R. Sieferle, *Rückblick auf die Natur. Eine Geschichte des Menschen in seiner Umwelt* (München 1997) 91-92.

7 Malanima, *Energia*, 107.

2. Numbers and energy output

Any statement about the role of windmills in the energy supply of pre-industrial Europe presupposes that both the numbers and the energy output of windmills are known, or at least: can reliably be guessed. Is that really the case? While we do have some state-wide counts of numbers of windmills in the nineteenth and early twentieth centuries (see Appendix I), published counts from the period before 1800 are in fact exceedingly scarce. The total of 30,000 – 100,000 windmills in early modern Europe given by Malanima is not based on actual data on numbers of mills, but derived from estimates about the total capacity of waterwheels and windmills.⁷ The era of the introduction and spread of the vertical windmill into most parts of Europe between about 1180 and 1350, seems to have been more intensely studied than the period between the High Middle Ages and to the beginning of the nineteenth century. The evolution in the only country for which we have more detailed figures from the early modern period, namely the Northern Netherlands, is in all probability not representative for Europe as a whole. Regional and local data from various parts of Europe rather suggest, that renewed growth in the numbers of windmills did not start until the eighteenth century and continued well into second half of the nineteenth century. Richard Hills surmises that the number of windmills in England probably doubled between 1760s and the 1820s.⁸ In the Hungarian plains, László Makkai tells us, the diffusion of wind-powered corn mills did not really take off until after 1850.⁹

Turning to data on the energy output of windmills we find ourselves no more on solid ground than with the evidence on numbers. Although the secondary literature is less sparing with estimates of the energy output than with facts on the total numbers of windmills, the picture remains confused. In fact, we are faced with an embarrassment of riches, as Appendix II shows. This appendix gives an overview of the data on the energy output of windmills in the Late Middle Ages and early modern period (column 3) to be found in the most relevant general and more specialist works on the subject (column 1), together with their source (column 4) and the period and category of windmills to which they are said to apply (column 2). There is evidently a bewildering variety of estimates. The literature yields a wide range of figures from which to choose. The spectrum runs from an estimate of 1 kW (or slightly more than 1 h.p.) for a common post mill in the Middle Ages (Smil 1994) to an estimate of 112 kW (or almost 150 h.p.) at the windshaft, calculated for a tower mill in the eighteenth century with a wing span of 20 metres, at a wind

8 R. L. Hills, *Power from wind. A history of windmill technology* (Cambridge 1994) 77-78; see also appendix I.

9 L. Makkai, 'Productivité et exploitation des sources d'énergie (XIIe – XVIIe siècle)', in: S. Marriotti (ed.), *Productività tecnologia nei secoli XII-XVII* (Florence 1981)181.

speed of 10 m./s (Smil 1994). By way of comparison: waterwheels in England and France in the eighteenth century had an average energy output of 6.5 h.p. and those in Central Europe, according to an estimate from about 1800, between 4.2 and 7.4 h.p.¹⁰

There is no a priori reason to assume that the lower estimates in Appendix II should be more valid or at least 'closer to the truth' than the higher ones, or vice versa. The fact that some figures are more often cited than others does not automatically lend them a higher degree of credibility. In the widely quoted article by J.W. de Zeeuw on the role of peat as a source of energy in the Dutch Golden Age, for instance, the importance of windpower is minimized with the argument that 'the total of 30,000 windmills ... at work around the Northsea' by 1900 'represented a constant effect of 100 megawatts, an average of 3.33 KW per mill' and the estimated 3,000 – 4,000 windmills operating in the Netherlands in the seventeenth century, being 'less effective' than those about 1900, will have had an energy output of 2.5 kW as an average.¹¹ But the work quoted by De Zeeuw in support of his argument, a lecture given by C. Daey Ouwens at the Technical University of Eindhoven in 1973, does not specify the source of these data.¹² One wonders, indeed, how Daey Ouwens arrived at the exact figure 30,000 mills 'around the North Sea' (which part of England was included, for example, or which part of Germany?) and computed their total capacity at 100 megawatt. The author leaves us in the dark.

The estimate provided by John Smeaton in a paper read to the Royal Society in 1759, which has the special aura of a figure calculated in the pre-industrial period itself (and by a great expert on energy, at that), also seems to enjoy a much greater weight in the secondary literature than the evidence can bear. Smeaton, after all, never did measure the actual energy output of Dutch windmills. What he really did, was to calculate on the basis of a series of experiments with a small-scale model the effect produced by various wind speeds upon sails of different surfaces and set according to different methods of weathering. According to these calculations, the effect produced by enlarged sails of 30 feet radius, set according to the best method of weathering, should be nearly twice as large than the effect produced by common Dutch sails of the same length, namely 3.66 h.p. versus 2 h.p. These theoretical and experimental results were then not corroborated by a test with a life-size Dutch windmill, but a comparison between the performance of an

10 T. Reynolds, *Stronger than a hundred men. A history of the vertical water wheel* (Baltimore 1983) 176-179; the average for England and France excludes the (exceptionally powerful) wheel at Marly.

11 J.W. de Zeeuw, 'Peat and the Dutch Golden Age. The historical meaning of energy-attainability', in: *AAG Bijdragen* 21 (1978) 4, 19-20.

12 C. Daey Ouwens, 'Overige energiebronnen', in: H.J.M.Beurskens, *Energie, Studium Generale Technische Hogeschool Eindhoven* (Eindhoven 1973) 76.

(English?) wind-powered oil mill, equipped with enlarged sails of 30 feet radius, with that of a horse-powered oil mill proved the former to go twice as fast as the latter.¹³ Inferences about the energy output of eighteenth-century Dutch windmills in general, regardless of size and type, seem therefore to be unwarranted.

The sober conclusion from the range of data collected in Appendix II is, that the energy output of a windmill can only adequately be estimated if we have precise information on many different variables. Apart from the span of the sails and the method of weathering, we should also know how a mill performed at various wind speeds and at which point of the mill a particular achievement was measured: at the windshaft or down below, where the force of the wind was harnessed to keep devices like a scoopwheel, a millstone, a set of saw blades or a couple of runners in motion. In order to assess the contribution of windmills to the total energy supply in a given area in a given period, we should, in addition, be informed about the distribution of the total number of windmills according to different sizes and types and about the frequency of various wind speeds in the course of the year (and thus the frequency with which a windmill might operate at a particular level of performance). Richard Hills remarked, for instance, that according to present-day measurements the total number of hours per year with wind speeds at which windmills could work (6 – 12 m/sec) is higher in Holland than in the English Fens - 2,671 versus 2,228) and that the difference in the number of hours at which windmills could work most effectively (8 – 12 m/sec) was even greater (1,339 in Holland versus 450 in the Fens).¹⁴ Changes in the composition of a windmill population and variations in frequency of wind speeds could significantly affect the total energy output of windmills. Collecting such data will of course be far from easy, but is not impossible. Without them, statements about the energy output of windmills in the past will only remain a random guess.

3. The uses of windmills

The data in Appendix II are as far as possible specified by category of windmills. Windmills were after all not a monolithic mass. They could serve a variety of purposes. Like waterwheels, windmills were originally employed for grinding corn. From 1407/08 onwards (when the first *poldermolen* was built near Alkmaar, Holland), windpower was also regularly employed for drainage.¹⁵ And *pace* Rolf Siefert-

13 J. Smeaton, 'An experimental inquiry concerning the natural powers of water and wind to turn mills and other machines', in: *Philosophical Transactions of the Royal Society* LI (1759), part 1, (London 1760); 144-168.

14 Hills, *Power from wind*, 151.

15 A. Bicker Caarten, *Middeleeuwse watermolens in Hollands polderland 1407/08 – rondom 1500* (Wormerveer 1990) 44-56.

le, the uses of windmills did not remain restricted to the 'less complicated' operations of grinding corn or raising water. Appendix III shows that the industrial applications of windmills in the early modern period were vastly extended. As far as the variety of uses was concerned, windmills were well-matched to waterwheels.

The message of this comparison between waterwheels and windmills can also be reversed. If most of the industrial applications of waterwheels could evidently also be performed by windmills, why did it take so long before these applications were brought into practice? It was more than merely a matter of taking the apparatus out of a waterwheel and plugging it in a windmill. Making the applications work in a windmill required more or less substantial modifications, not only because one had to reckon with the fact that wind as a power source was more unsteady than water and that the axle (windshaft) of a windmill (in many areas in Europe, at least) stood in an inclined position, high above the ground, instead of being placed, as in watermills, in a horizontal position at roughly the same level as the attached equipment, but also, as Richard Hills has pointed out, because one had to take into account 'the particular restraints of a cramped building that needed to present as small as possible an obstruction to the wind'.¹⁶

When the new applications eventually materialized, this wave of innovations was largely concentrated in a rather small part of Europe (Holland) and in a relatively brief period of time (between c. 1580 and c. 1680). Why did the leap forwards occur in Holland and why did it take place in exactly this period? The short answer is of course that (1) Holland during this period went through a unique spurt of economic growth and therefore, presumably, needed a huge extra amount of energy (including motion energy); (2) given the physical make-up of the coastal provinces of the Netherlands, waterwheels could not provide an answer to this expanding demand (except for a few tide-mills);¹⁷ (3) human power was growing rapidly more expensive, witness for instance the doubling of the wages of sawyers between 1580 and 1610;¹⁸ and (4) there was already a group of craftsmen with experience in building windmills for another task than for the common job of grinding corn, namely for raising water.

Even so, the massive transition to windpower in industry was not a foregone conclusion. All the new applications in industry, just like the tasks of raising water and grinding corn¹⁹, could after all also have been realized by means of horse-mills. And some of them, such as oil pressing, fulling or canon boring, have in fact to some extent been performed with the aid of horse-power. According to the De

16 Hills, *Power from wind*, 165.

17 A. Tutein Nolthenius, 'Getijmolens in Nederland', in: *Tijdschrift KNAG* 71 (1954) 186-200.

18 J. de Vries, 'The labour market', in: K. Davids and L. Noordegraaf (eds.), *The Dutch economy in the Golden Age. Nine studies* (Amsterdam 1993) 62-63, 73.

19 Bicker Caarten, *Middeleeuwse watermolens*, 26-31.

Zeeuw's calculations (assuming a total of 3,000 industrial windmills, an energy output per windmill of 2.5 kW, and a working time per windmill of 24 hours a day), the replacement of all industrial windmills in the Dutch Republic by horse-mills would have required the use of 50,000 horses.²⁰ The problem was probably not that such a number of horses in the Northern Netherlands in the sixteenth and seventeenth century could not be found, or not be fed. Ludovico Guicciardini remarked during his journey through the Low Countries about 1560 that the country, 'and in particular Holland, Friesland, Gelderland and Flanders' produced 'a tremendous number of big, brisk and strong horses' and surveys about the Veluwe and Overijssel in the sixteenth and early seventeenth centuries revealed the presence of a larger number of horses than could be explained by the regular needs of farming.²¹

The sticking point for a large-scale shift to horsepower in industry after 1580 may rather have been that the demand for horses from the agricultural sector was topped by an increased demand from the military. Between about 1570 and 1650 and again between c. 1670 and 1710 the Northern Netherlands was almost continuously at war. Up to about 1630, and again in the 1670s, the eastern provinces of the Dutch Republic were moreover the scene of operation of two opposing armies. Now, armies on the march always required a great number of horses, not just for employment in the cavalry, but also for drawing the huge train of artillery and baggage carts.²² Even the Dutch army, which since the days of Prince Maurits made a relatively extensive use of transport by water, during its campaign in Brabant in 1602 had a train of 3,000 carts (to supply 24,000 men), which must have meant a far larger number of horses.²³ It may be surmised (although data on the market in horses are still sorely lacking) that the demand from the military, on top of the regular demand from farmers, pushed up the prices of horses from the 1580s, just like it did in another period of almost uninterrupted warfare, between c. 1793

20 De Zeeuw, 'Peat', 19-20.

21 K. Davids, *Dieren en Nederlanders. Zeven eeuwen liefen lied* (Utrecht 1989) 15, B.H. Slicher van Bath, *De agrarische geschiedenis van West-Europa 500-1850* (Utrecht/Antwerpen 1976³) 318-322, H.K. Roessingh, 'De veetelling van 1526 in het kwartier van Veluwe', in: *AAG Bijdragen* 22 (1979) 8-12, 35-36, J.L. van Zanden, 'De telling van de veestapel en de graanproductie in Zwollerkerspel in 1526. Een stukje van de legpuzzel', in: *AAG Bijdragen* 28 (1986) 96-99.

22 J.W. Wijn, *Het krijgswezen in den tijd van Prins Maurits* (Utrecht 1934) 385, Braudel, *Civilisation*, dl. I, 304-305, G. Parker, *The military revolution. Military innovation and the rise of the West, 1500-1800* (Cambridge 1988) 69-71, O. van Nimwegen, *De subsistentie van het leger. Logistiek en strategie van het Geallieerde en met name het Staatse leger tijdens de Spaanse Successieoorlog in de Nederlanden en het Heilige Roomse Rijk (1701-1712)* (Amsterdam 1995) 11-12.

23 Wijn, *Krijgswezen*, 380-381, 387.

and 1815.²⁴ ‘Crowding out’ on the horse-market may have made the shift to wind-power after 1590 the more attractive proposition.

Although the share of windmills for other uses than grinding corn probably nowhere else became as large as in Holland (but again, exact data are lacking), industrial mills and drainage mills have been in operation in many other countries as well. The use of windpower for industry and drainage was not a purely Dutch phenomenon. The Netherlands nevertheless after about 1570 succeeded Flanders and northern France as the principal centre of diffusion of innovations in windmill technology.²⁵ Between the end of the sixteenth century and the last quarter of the eighteenth century, it was Dutch millwrights who played the leading role in the spread of wind-powered mills for drainage and industry in various parts of Europe.

Before this time, Dutch influence was evident as well, but still worked in more indirect ways. As early as 1425, for instance, the magistrate of the town of St.Omaars in Artois, faced with the problem of draining marshes in the surrounding countryside, sent a delegation to Holland to fetch the plan of a mill ‘pour vider les eaux’. A drainage mill actually came into operation near this city in 1438.²⁶ Although the new type of mill in this environment proved to be a failure – it was put out of use in the early 1450s – this did by no means signal the end of the spread of drainage mills. Drainage mills on the Dutch model were introduced into the Polish part of Prussia and into Schleswig-Holstein from the later sixteenth century onwards²⁷ and were adopted at several places in Flanders and the adjacent region in France (including St.Omaars), in Ost-Friesland (Germany) as well as in the Fens and the Norfolk Broads in England during the seventeenth and eighteenth centuries.²⁸

24 J. de Vries, *Barges and capitalism. Passenger transportation in the Dutch Economy (1632-1839)* (Utrecht 1981) 136-137.

25 On the pioneering role of this region in the early phase of windmill technology see Y. Coutant, ‘L’étude des moulins à vent médiévaux: nouvelles pistes’, in: *Revue du Nord* 74 (1992), 5-24 and J.P.A. Stroop, *Molenaarstermen en molengeschiedenis* (Arnhem 1979). One of the most important innovations originating from Flanders was the windmill brake, see e.g. Y. Coutant and P. Groen, ‘The early history of the windmill brake’, in: *History of Technology* 19 (1997) 1-17.

26 A. Derville, ‘Le marais de Saint Omer’, in: *Revue du Nord* 62 (1980) 83.

27 K. Davids, ‘The transfer of windmill technology from the Netherlands to North-Eastern Europe from the 16th to the early 19th century’, in: J.Ph.S. Lemmink and J.S.A.M. van Koningsbrugge (eds.), *Baltic affairs. Relations between the Netherlands and North-Eastern Europe 1500-1800* (Nijmegen 1990) 36-37.

28 L. Devliegher, *De molens in West-Vlaanderen* (Tielt 1984) 80-85, L. Denewet, ‘De hoos-molen te Gent-Drongen’, in: *Molenecho’s* 12 (1984) 3, 8-9, 16, C. Rivals, *Le moulin à vent et le meunier dans la société traditionnelle française* (Ivry 1976) 117-125, Hills, *Power from wind*, 136-165.

The spread of industrial mills from Holland began around 1620 and accelerated after 1700. Wind-powered oil mills were built by Dutch millwrights in Denmark, England, Ireland, Sweden and North-west Germany, paper mills in England and the Southern Netherlands, hulling mills in North-west Germany, saw mills in the Southern Netherlands, Sweden, Russia, the Baltic lands and Portugal.²⁹ By the middle of the eighteenth century, the outflow of windmill technology from the Dutch Republic had grown to such a degree that the States General in February 1752 resolved to put a complete ban on the export of windmills. Henceforward, no one was allowed to assist in the sale, construction or transport of any part of a Dutch windmill on the order of a foreign customer, or to export any tool that could be used to build them. An exception was made only for drainage mills, twenty years later.³⁰ Although Dutch windmill technology for a long time thereafter kept to be regarded as a model worth imitating, it was increasingly brought into practice by foreigners themselves, instead of being transferred by craftsmen from the Netherlands. The *holländer*, *holländare* and *Holländermühle*, which in the later eighteenth century and nineteenth centuries became such a familiar sight in large parts of Northern Europe, were no longer built by Dutchmen. And from the end of the eighteenth century onwards, it was England that took the place of Holland as the leading centre of innovation.

4. Evolution in performance

Windmills in the early modern period were not only put to a variety of uses, but also showed an evolution in performance. In a pioneering article on ‘molinology and economic history’ published in 1986, Chris Vandenbroeke calculated that a corn windmill in Flanders in the early nineteenth century probably produced nearly 70 % more flour per year than a wind-driven corn mill in the first half of the fifteenth century.³¹ The possibilities for improvement in performance during the

29 Davids, ‘Transfer of windmill technology’, 37-45, 49, K. Davids, ‘Successful and failed transitions. A comparison of innovations in windmill-technology in Britain and The Netherlands in the early modern period’, in: *History and Technology* 14 (1998) 228-231, K. Davids, ‘The transfer of technology between Britain and The Netherlands, 1700-1850’, in: J.R. Bruijn and W.F.J. Mörzer Bruyns (eds.), *Anglo-Dutch mercantile marine relations 1700-1850. Ten papers* (Amsterdam/Leiden 1991)10, Hills, *Power from wind*, chapter 7.

30 Davids, ‘Transfer of windmill technology’, 41, 49. The immediate cause for the issue of the prohibition order in 1752 were the efforts in the Southern Netherlands to establish a native timber processing industry with the help of technology imported from the Netherlands. On the reasons for the failure of earlier attempts to obstruct the export of windmill technology see Davids, ‘Transfer of windmill technology’, 48.

31 C. Vandenbroeke, ‘Molinologie en economische geschiedenis: enkele terreinverkenningen’, in: *Handelingen van de Maatschappij voor Geschiedenis te Brugge* (1986); 15-16.

early modern period were apparently by no means slight. And corn mills in Flanders were, for all we know, by no means in the forefront of advance in windmill technology in Europe. The main centres of innovation during most of the early modern period after all resided in Holland and later in England.

Windmills in Holland showed improvements in performance in several respects. In his comparative survey on the output of windmills presented to the Royal Society in 1759, John Smeaton noticed that the best windmills appeared to be those weathered in the Dutch manner 'where the extremities (of the sails) stood at an angle of $7\frac{1}{4}$ (degrees) with the plane of a motion' (except for windmills weathered in same manner, equipped with broadened sails).³² His conclusion was based on a series of experiments 'of various structures, positions and quantities of surface' of windmill sails with a small-scale model. By the time of Smeaton's observations, this specific design of the sails of Dutch windmills was probably more than a century old. In the late sixteenth and early seventeenth centuries, millwrights in Holland began to move the position of the sail-bars in such a way that the sail-arm did no longer hold the sail-bars in the middle, as had been usual in sail design, but was now off-centre. Sail-bars were thus put at one side of the sail-arm across the entire length of the arm, and in varying angles. The variation of the angles could differ by type of mill. This particular form of sails, known as weathering in the 'Dutch manner', permitted sails to catch more wind than was achieved with sails of a traditional design, even if they still attracted much less of all the available windpower than the nearly 60 % claimed by Vaclav Smil and other authors as theoretically possible.³³

Smeaton's model gave only a partial view. It did not take account of a number of other improvements in performance which had taken place in the preceding two centuries or so, in particular in Holland. First of all, measures were taken to diminish the disparity between the energy output at the windshaft and the useful output of the mill, and thus to enhance its effectiveness as a source of power, by improvements in the gear. As in the case of waterwheels³⁴, friction between parts of the gear of windmills was little by little reduced. Patent applications dating from the first half of the seventeenth century and 'mill books' published between c.1680 and 1760 bear witness to sustained efforts of carpenters, millwrights and engineers to arrive at the optimal shape, position and number of cogs and staves, to prevent breakage of cogs and wheels and to determine the ideal measures of wheels and pinions. Pieter Limpergh's *Architectura Mechanica Moole boek*, published in 1686,

32 Smeaton, 'Experimental inquiry', 145-148.

33 H.A.Visser, *Zwaaiende wieken* (Wormerveer 1946) 53-54, A.Bicker Caarten, *Zuid-Hollands molenboek*, (Alphen aan de Rijn, 1965 ?), p.53, R.J. Forbes (ed.), *The principal works of Simon Stevin*, dl. V (Amsterdam 1966) 314-322, Smeaton, 'Experimental inquiry', 144, 147, Hills, *Power from wind*, 81-86, Smil, *Energy*, 153.

34 Malanima, *Energia*, 108-109.

for example, gives detailed descriptions and illustrations of the current methods in Holland to design cogs and measure off their distribution along a wheel. Johannes van Zyl's widely used *Theatrum machinarum univemale, of groot-algemeen moolen-boek*, published in 1734, contained an 'Exact notice of a mathematical order of all kinds of gear'.³⁵ Secondly, new designs for the hulls of windmills appeared that could provide an adequate solution for the very problem defined by Richard Hills: present as small as possible an obstruction to the wind and yet contain enough space to accommodate all, or part, of the equipment which was kept in motion by the turning of the sails. The most widespread new hull-design was the so-called octagonal smockmill (*achtkante bovenkruier*), first developed in Holland in the early sixteenth century, which in many countries of Europe came to be known as the archetypal Dutch windmill, the *hollænder*, *holländare* or *Holländermühle*.³⁶

The equipment driven by wind energy evolved as well. Although machines or other devices installed in windmills were initially modelled on those used in watermills, the nature and capacity of the equipment often substantially changed in course of time. Whereas pumping devices moved by waterwheels (and a few used in early windmills) often consisted of a row of buckets on a chain, most of the wind-powered drainage mills up to the second half of the eighteenth century were provided with a single vertical scoopwheel. The main alternative technique, which was probably first applied in small, horse-powered mills and later transferred to larger, wind-powered drainage mills, was to raise water by means of an Archimedean screw. This type of drainage mill, called a *vijzelmolen*, could lift water more than twice as high as a mill fitted out with a vertical scoop wheel: four to five metres instead of one and a half or two metres. Although it was first introduced in a few polders in Holland in the mid-seventeenth century, the *vijzelmolen* did not spread more widely in Holland and other parts of the Netherlands (and beyond) until later in the 18th century. Another variant which emerged in Holland in the late eighteenth century (and was applied in a few windmills as well), was a scoopwheel placed in an inclined, instead of in a vertical position.³⁷

Equipment used in industrial mills did no more remain static than appliances employed in drainage mills. Wind-driven sawmills, which spread in Holland from the 1590s onwards, were provided with a number of frames, fitted with sets of

35 Forbes (ed.), *Principal works*, pp. 42-63, P. Limpergh, *Architectura Mechanica Moole boek* (Amsterdam [1686]), J. van Zyl, *Theatrum machinarum univemale, of groot-algemeen moolen-boek* (Amsterdam 1734) 12, Davids, 'Transfer of windmill technology', 43-44.

36 Hills, *Power from wind*, 65-73, A. Sipman, *Molenbouw. Het staande werk van de bovenkruiers* (Zutphen 1990) 94-105.

37 G.H. Keunen, 'Waterbeheersing en de ontwikkeling van de bemalingstechniek in West-Nederland', in: *Bijdragen en Mededelingen betreffende de Geschiedenis der Nederlanden* 103 (1988) 577.

fine-blade saws and operated with the aid of a triple-throw crankshaft.³⁸ Oil-pressing windmills in Holland were from the seventeenth century onwards equipped with a more complex system of mechanisms than was commonly used in this type of mill before, including a pair of huge edge runners and up to two sets of presses and six vertical stampers.³⁹ In the paper industry, 'hollander' beaters (tubs with rotating drums fitted out with metal bars to cut up rags) were first installed in windmills for the making of blue paper in the Zaanstreek in the 1650s and were since about 1670 adapted for the production of high-quality, white paper as well.⁴⁰ All such improvements were first introduced in windmills in Holland and later adopted in watermills in other countries of Europe. For a long time, it were millwrights from the Dutch Republic, skilled in the building of windmills, who were the preferred experts to construct and install these devices in watermills in England, France, Germany, Norway, Sweden or Russia.⁴¹ Thus, even if the technology of industrial windmills initially built on the achievements realized in watermills, improvements developed in windmills in the later seventeenth and eighteenth centuries contributed to enhance the physical productivity and/or increase the quality of products of watermills.

None of these technical improvements was made on the basis of a theoretical investigation into the power of wind. The most penetrating, general study on windmills to be made in The Netherlands before the 1750s, viz. the notes on cogs and staves composed by the engineer Simon Stevin about 1600⁴² was not known among a wider public until the late 1660s and did not exert any perceptible influence at the time. The body of knowledge on windmills up to the middle of the eighteenth century was still almost entirely of an empirical nature. The art of the millwright was only partly transmitted by script or drawing and was never completely disseminated in print. Even the magnificent 'mill books' did not represent the full extent of the expertise of the millwrights. Innovation in windmill technology in the Netherlands was in reality largely a process of learning by doing, of advance by trial and error, of improvement by variation and selection; it evolved only to a limited extent through formal learning. This process was partly reflected in patent statistics. A large number of the patented inventions in the Dutch Republic related to windmills. Of all the inventions patented by the States General or the provincial states between 1580 and 1720 some 34 % referred to hydraulic equipment and

38 F.M. Rutten, 'De nuttelycke vindinge van het houtzagen. De octrooien voor houtzaagmolens van Cornelis Cornelisz. van Uitgeest', in: J.C. Coppens *et.al.*, *Vierhonderd jaar houtzagen met wind* (Sprang-Capelle 1996) 11-32, Hills, *Power from wind*, 166-171.

39 P. Boorsma, *Duizend Zaanse molens* (Wormerveer 1950) 42-47, Hills, *Power from wind*, 172-178.

40 H. Voorn, *De papiermolens in de provincie Noord-Holland* (-Haarlem 1960) 42-45.

41 Davids, 'Transfer of windmill technology', 37-43, Hills, *Power from wind*, chapter 7.

42 Forbes (ed.), *Principal Works*, 41-45.

installations (including drainage mills) and some 14 % to corn mills and other industrial windmills. The share of the latter category was especially high in the 1580s and 1590s (23 %) and in the 1620s and 1630s (18 %).⁴³ Among the patented inventions in these periods were – beside many novelties that were never applied at all – also such seminal improvements as the wind-powered sawmill, the ‘double’ oil mill and the drainage mill equipped with an Archimedean screw.

When windmills eventually, in the first half of the eighteenth century, *did* become the object of theoretical inquiries, it was scientists and engineers in France who assumed the leading role. Taking earlier work on waterwheels as their starting point⁴⁴, scholars like Antoine Parent, Henri Pitot, Bernard de Bélidor and Jean-Baptiste d’Alembert contributed to the development of theoretical insights about the relationship between the velocity of wind and the power of windmills. Yet, the French lead in theory no more gave millwrights from France an edge in the construction of windmills than it had provided them with a superior skill in the building of waterwheels. One of the reasons was no doubt that, as in the case of waterwheels, the early theory on windmills did not square with everyday reality. When a professor at the University of Leiden, Johan Lulofs, in the early 1750s, in collaboration with a surveyor of the drainage board of Rijnland Melchior Bolstra, compared the actual performance of drainage mills with the capacity as predicted by the current theories, he found that the mills in fact ‘*did far more* [italics mine] than the mathematical and mechanical theory promised, (which) proved the defectiveness of the latter’.⁴⁵ Scholarly interest in windmill technology in The Netherlands, which in the next few decades markedly grew, took a much more pragmatic twist than in France. Professors, engineers and surveyors concentrated on exact, statistical comparisons of empirical data on the useful output of different types of (mainly drainage) mills – for example, mills with a vertical scoop wheel versus mills with an inclined scoop wheel – rather than spending their time on abstract calculations or speculations.⁴⁶ They were more concerned with the ‘selection’ of the fittest mills than with the development of optimal designs for new mills. But the main improvements in windmill technology introduced in England between about 1750 and the end of the Napoleonic Wars were not inspired by current theories on wind power, either. The fantail for winding the mill, the self-acting shuttered sails, the

43 K. Davids, ‘Patents and patentees in the Dutch Republic between c.1580 and 1720’, in: *History and Technology* 16 (2000) 266.

44 Cf. Reynolds, *Stronger than a hundred men*, chapter 4.

45 J.Lulofs, ‘Wiskundige en werktuigkundige beschouwing der wind-molens’, in: *Verhandelingen van de Hollandsche Maatschappij der Wetenschappen* 2 (1755) 598-599.

46 K. Davids, ‘Universiteiten, illustre scholen en de verspreiding van technische kennis in Nederland, eind 16e – begin 19e eeuw’, in: *Batavia Academica. Bulletin van de Nederlandse Werkgroep Universiteitsgeschiedenis* 8 (1990) 11-22; cf. also E. Schultz, *Van zee tot land. Waterbeheersing van de Nederlandse droogmakerijen* (Lelystad 1992) 207-208.

governor for regulating the millstone, the iron sail-arm – these inventions emerged in a similar way as earlier improvements in Holland: from experience and trials in practice.⁴⁷

Once scientific theory in the nineteenth and twentieth centuries caught up with the art of the millwright, there emerged opportunities for further improvement in windmill technology, for instance in the design of sails or in the generation of electricity.⁴⁸ When the numbers of windmills in the early twentieth century sharply declined, they had by no means yet reached the upper limits of their evolution.

5. Conclusion

Future research on the history of windmill technology after 1500 thus should first get back to basics. We should have more data about the numbers and energy output of windmills, taking account of all the relevant variables mentioned above. We should also know more on the different uses of windmills in various parts of Europe and about the extent to which best-practice technology developed in successive centres of innovation (Flanders and northern France, Holland, England) was adopted (and perhaps adapted) in other countries in Europe.

Once the ‘basics’ are better known, the development of windmill technology after 1500 in its various aspects can be explained more effectively. This inquiry should consider the following: the costs and benefits of building and operating windmills compared with waterwheels, horse mills and steam engines⁴⁹, the growth or decline of population in a given region, and the extent and nature of institutional restrictions or incentives concerning the construction of windmills. If the numbers of windmills in many parts of Europe showed indeed renewed growth in the eighteenth century and reached their peak somewhere in the nineteenth century, it would not be far-fetched to suppose this expansion might have been related both to the vigorous population growth starting in the eighteenth century and to the progressive loosening after c. 1800 of institutional constraints such as corporate monop-

47 Davids, ‘Successful and failed transitions’, 232-233, Hills, *Power from wind*, 92-108.

48 K. Mulder, *De Hollandse molen, monument of werktuig ? Een onderzoek naar de controverse over het voortbestaan van de Hollandse windmolen* (Enschede 1987), part 2, Hills, *Power from wind*, 225-231.

49 As for instance was done by H.W. Lintsen, ‘Van windbemaling naar stoombemaling; innoveren in Nederland in de negentiende eeuw’, in: *Jaarboek voor de Geschiedenis van Bedrijf en Techniek* 2 (1985), 48-63, R. Holt, *The mills of Medieval England*, (Oxford 1988), chapter 5, and J. Langdon, ‘Water-mills and windmills in the west midlands, 1086-1500’, in: *Economic History Review* 44 (1991) 435-440.

lies, feudal privileges or mercantilist state policies that may have held back the growth in numbers of windmills during much of the early modern period.⁵⁰

50 See for example Hills, *Power from wind*, 77-78 and S.B. Ek, *Väderkvarnar och vattenmöllor. En etnologisk studie i kvarnarnas historia* (-Stockholm 1962), especially chapters 6-11.

Appendix I. Numbers of windmills, c.1500- 1900

Country, region	Cornmills	Other industrial mills	Drainage mills	All windmills combined
France				
Canton Arras only 1760	112	17		
Canton Arras only 1806	217	125		
Entire country 1847	c. 7,800			c. 8,700
England				
Sussex only early 18th c.				80
Sussex only 1823				190
Suffolk only c.1780				180
Suffolk only 1823				374
Suffolk only c.1838				430
Entire country c.1300				c. 4,000
Entire country c.1540				c. 2,000
Entire country c.1800				c. 10,000
Germany				
1882	18,579		c. 19,900	
1895	17,803		18,362	
1907	17,027		17,933	
Finland				
1585				753
1820				c. 7,500
The Netherlands				
Holland only c.1500			c. 215	
Holland only c.1630	365		222	
Holland only (except Westfriesland) c.1730		c. 1,230		
Holland only c.1800	306		c. 869 c. 1160	c. 2335
Groningen only 1770		100	few	
Groningen only c.1810		114	398	512
Groningen only 1860		197	more than 300	c. 500
Entire country				
1850	1,920			
1860	2,204			
1878	2,311			
1890	2,391			
1896			1,953	

Country, region	Cornmills mills	Other industrial	Drainage mills	All windmills combined
Belgium				
West-Vlaanderen only c.1775	605			
West-Vlaanderen only 1846	1,007			
West-Vlaanderen only 1880	759			
Entire country 1846				2,739
1880				2,158

Sources:

France: Rivals, *Le moulin à vent*, 107; Hills, *Power from wind*, 75-77

England: J. Langdon, 'The birth and demise of a medieval windmill', *History of Technology* 14 (1992), 55; G.N. Von Tunzelmann, *Steam power and British industrialization to 1860* (Oxford 1978) 122-123; Hills, *Power from wind*, 75, 79; the number of windmills in England in 1540 was kindly communicated by prof.dr. John Langdon.

Germany: J.C. Notebaart, *Windmühlen. Der Stand der Forschung über das Vorkommen und den Ursprung* (Den Haag/Parijs 1972) 64.

Finland: Notebaart, *Windmühlen*, 93.

The Netherlands : Algemeen Rijksarchief The Hague, Collectie Goldberg 45, Financier van Holland 464, 559; Bicker Caarten, *Middeleeuwse watermolens*, passim; S. Hart, *Geschrift en getal* (Dordrecht 1976) 26; J.A. de Jonge, *De industrialisatie in Nederland tussen 1850 en 1914* (Nijmegen 1976²).218; Lintsen, 'Van windbemaling naar stoombemaling', 50 (note); R.F.J. Paping, 'Industriële windmolens op de Groninger klei, 1770-1860', *Jaarboek voor de Geschiedenis van Bedrijf en Technie*, 9 (1992) 93; P. Priester, *De economische ontwikkeling van de landbouw in Groningen 1800-1910. Een kwalitatieve en kwantitatieve analyse*, (Wageningen 1991) 274-277; A.M. van der Woude, *Het Noorderkwartier. Een regionaal-historisch onderzoek in de demografische en economische geschiedenis van westelijk Nederland van de late Middeleeuwen tot het begin van de negentiende eeuw* (Utrecht 1983²) 320-325.

Belgium: De Vliegheer, 'Molens in West-Vlaanderen', 16; Notebaart, *Windmühlen*, 47.

Appendix II. Energy output of windmills

Author	Category of windmills, period	Energy output per windmill	Source of data
<i>General</i>			
Cipolla 1962/1974	Average range	10 – 30 h.p.	Not given, probably Forbes
Braudel 1979	Average range ?	5 – 10 h.p.	Not given
Makkai 1981	Average range ?	10 – 30 h.p.	Not given, probably Forbes/Cipolla
Smil 1994	Common post mills in Middle Ages	1- 2 kW	Not given
Smil 1994	Post mills	1.5 – 6 kW	William Rankine 1866
Smil 1994	Tower mills	4.5 – 10.5 kW	William Rankine 1866
Unger 1984	Mid-18th century mills	2 h.p. = 1.5 kW	Calculations by John Smeaton 1759
Malanima 1996	Late 18th century mills	5- 10 h.p. = 3.7 – 7.5 kW	Not given, probably Braudel
Smil 1994	Tower mills 18th century (wing span 20 metres)	112 kW (theoretically) at wind speed of 10 m/s, useful output less than 40 kW	Calculations by author
Daey Ouwens 1973	Windmills around the Northsea c.1900	30,000 windmills with total average capacity of 100 Megawatt	Not given
De Zeeuw 1978	Windmills around the Northsea c.1900	3.3 kW	Daey Ouwens 1973
<i>Dutch</i>			
Smil 1994	mid-17th century Dutch drainage mill	30 kW at windshaft, useful output less than 12 kW	Modern measurements
Forbes 1958/1966	Dutch drainage mill c.1648 (wing span 48 feet)	40 h.p. at windshaft, 15.6 h.p. at scoopwheel, at wind speed of 8-9 m./s	Measurements in 1942
De Zeeuw 1978	Average Dutch windmill 17th century	2.5 kWh or 60 kW per windmill per day	Backward extrapolation by author
Hills 1994	Large Dutch drainage mills 17th century	20 effective h.p. at the scoopwheel in very favourable wind conditions	Not given
Malanima 1996	Dutch windmills, 17th century	60 kW per windmill per day	Estimate by De Zeeuw 1978
Forbes (ed.) 1966	Corn-grinding post mill c. 1735	6 – 10 h.p.	Calculations by author
Forbes 1958	Common Dutch windmill, 18th century (wing span 100 feet)	10 h.p.	Calculations by John Smeaton, modern measurements

Author	Category of windmills, period	Energy output per windmill	Source of data
Hills 1994	Best Dutch windmills mid 18th century	2 h.p.	Calculations by John Smeaton 1759
Schultz 1992	Dutch drainage windmills late 19th century	18.5 kW at strong wind, on average 11.8 kW	Measurements in Holland, c.1885
Hills 1994	Traditional (drainage) windmills	50 h.p. at windshaft at wind speed of 8 m./s, 60- 90 h.p. at windshaft at wind speed of 10 m./s.	Measurements in Holland, c.1930
Schultz 1992	Old Dutch drainage mills	3.7 – 4 kW at average wind speed	Measurements in Holland c.1940
Schultz 1992	Large Dutch drainage mills	Maximum 37 kW	lecture course on drainage, Agricultural University Wageningen, 1968
<i>English</i>			
Von Tunzelmann 1978	Average drainage mills Fens	3 h.p.	Not given
Hills 1994	Best drainage windmills in the Fens (UK)	40 h.p. with sufficient wind	Based on estimates late 18th, early 19th century
Von Tunzelmann 1978	Drainage mills in England (wing span 70 feet)	6.5 h.p.	Calculations by C.F. Parrington 1822

Note: the purpose of this appendix is to present an overview of data on the energy output of windmills as given in printed sources and secondary literature on windmills, not to suggest an interpretation of these data; I have therefore refrained from converting kilowatts into horsepower, or vice versa.

Sources: Braudel, *Civilisation*, dl. I, 308; Cipolla, *Economic history*, 52; Daey Ouwens, 'Overige energiebronnen', 76; Forbes, 'Power to 1850', 157-159; Forbes (ed.), *Principal works*, 319-322; Hills, *Power from wind*, 86-91, 128-129, 151-153; Makkai, 'Productivité et exploitation', 181; Malanima, *Energia*, 106; R.W. Unger, 'Energy sources for the Dutch Golden Age: Peat, wind and coal', *Research in Economic History* 9 (1984) 228-229; Schultz, *Van zee tot land*, 206-207, Smil, *Energy*, 112, 152-153; Von Tunzelmann, *Steam power*, 123; De Zeeuw, 'Peat', 4, 20.

Appendix III. Emergence of new industrial applications of the vertical water wheel and the vertical windmill

Type of mill	Waterwheel Date of first occurrence	Location	Windmill Date of first occurrence	location
Beer (malt ?)	831	NW France		
Hemp	990	SE France	1589	Holland
Fulling	1008	N Italy	c. 1620	Holland
	820	Switzerland ?		
Iron	1025 ?	S Germany		
	1197	S Sweden		
Iron-grinding			c. 1677	Holland
Oil	c.1100	SE France	Before 1550	Flanders/NW France
Ore-stamping	1135	N Italy		
Tanning	1138		1st quarter 17th century	Holland
Washleater			1592	Holland
Sugar	1176 ?	Sicily ?		
Cutlery (grinding and polishing)	1204	NW France		
Saw	1204	NW France	1592	Holland
Mechanical bellows	1214	Styria	?	Austria ?
Mustard	c.1250	SE France	c.1630-1675	Holland
Poppy	1251	NW France		
Paper	1276	N Italy	1586	Holland
Mine-pumping	1315	Moravia	c. 1550	South Germany ?
Pumping seawater In salt pans			1772	Scotland ⁵¹
Mortar	1321	S Germany	c.1628	Holland
Trass			c.1630-1660	Holland
Turning (lathes)	1347	SE France		
Pigment (paint)	1348	NW France		
Brasilwood			1601	Holland
Blue			1st quarter 17th century	
White lead			c. 1630	Holland
Blast furnace	1384	Belgium		
Pipe-boring	c.1480	S Germany		
Canon-boring			c. 1689	Holland

51 I am grateful to prof.dr. T.C. Smout for the reference to the windpump used in the salt-pan in St.Monance, Fife, Scotland.

Type of mill	Waterwheel Date of first occurrence	Location	Windmill Date of first occurrence	location
Rolling and slitting copper	1443	Central France		
Wire-drawing	1351 ? 1489	S Germany S Germany		
Gem-polishing	1534	NW France		
Coin	1551	NW France		
Hulling			1st quarter 17th century	Holland
Gunpowder			1st quarter 17th century	Holland
Stone-sawing			c. 1658	Holland
Tobacco/snuff			c. 1660	Holland
Cacao			18th century	Holland/Zeeland

Sources:

For waterwheels: Reynolds, *Stronger than a hundred men*, 94.

For windmills: Boorsma, *Duizend Zaanse molens*, 38-69, 170, 179; G. Doorman, *Octrooien voor uitvindingen in de Nederlanden uit de 16^e-18^e eeuw* (Den Haag 1942) 89, 91, A.Derville, 'Moulins, cultures industrielles et marchands dans les campagnes artésiennes et flamandes', *Revue du Nord* 72 (1990) 576, 587-589; Hart, *Geschrift en getal*, 24-27; A. Heerding, *Cement in Nederland* (Amsterdam 1971) 23-24, Hills, *Power from wind*, chapter 7; J.H. van den Hoek Ostende, 'Chocolaadmolens', *Jaarboek Amstelodamum* 71 (1979) 65-68, G.J. Honig, 'De molens van Amsterdam', *Jaarboek Amstelodamum* 27 (1930) 107-108, 117-121; J. Lewis, 'The excavation of an 18th-century salt-pan at St. Monance, Fife', *Proceedings of the Society of Antiquaries of Scotland* 119 (1989) 361, 367; Visser, *Zwaaïende wieken*, 105-109, 114, 118, 125-130.