

## Dung, sludge and landfill : biogas technology in the Netherlands, 1970 - 2000

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# Dung, Sludge, and Landfill

## Biogas Technology in the Netherlands, 1970–2000

**ROB RAVEN and GEERT VERBONG**

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The three decades following World War II witnessed unprecedented economic expansion and accelerated industrialization in the Netherlands. The foundation for this explosive growth had been laid in the aftermath of the First World War, before economic depression and then war again intervened. Beginning in the late 1940s, industry rapidly came to dominate the Dutch economy; chemicals and food processing in particular became internationally competitive sectors. Geography contributed greatly to these developments. Dutch harbors (in particular Rotterdam) and transportation infrastructure connected the Atlantic to the German Ruhr, and an emerging petrochemical industry helped fuel the German *Wirtschaftswunder*. Petroleum and natural gas supplanted coal as major sources of energy and raw materials, and the discovery of large quantities of natural gas in the northern Netherlands in the late 1950s gave another boost to industrial development. Energy-intensive industry was attracted to the region, and natural gas provided feedstock for the chemical industry. Agriculture was also being rapidly transformed from a fairly traditional economic sector to a highly modernized and industrialized provider of raw materials for the food-processing industry and agricultural exports. Agro-business produc-

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tivity rose dramatically, fueling an enormous increase in output even as farm-related employment steadily declined.<sup>1</sup>

By the mid-1960s this process of economic modernization was largely complete—and, as in other industrialized countries, its negative side effects were becoming increasingly clear. Industrial emissions caused significant air and water pollution, with attendant health risks. The expansion and concentration of the “bio-industry” (as factory farming of chickens, pigs, and cattle came to be called) produced huge quantities of dung and acrid odors. And all this vigorous economic activity generated a mighty torrent of waste that had to be removed and processed. Though all industrialized nations face the waste problem, several factors intensified its effects in the Netherlands: it is a small country with a large population; its most important industrial areas lie in the densely populated west and south; and the national economy is especially concentrated on energy-intensive industry, chemicals, and bio-industry.<sup>2</sup>

How did Dutch society react to the increasing waste stream? How did technology help manage it? How did environmental technologies interact with the changing social context? In this article we will seek to answer these questions by examining three related environmental technologies used in the anaerobic digestion of organic wastes. These technologies followed different paths from conception to implementation, and by reconstructing their evolution we will illuminate the complicated interplay between technological development and social context.

## The Waste Regime

In the late 1960s, waste treatment options mainly consisted of dumping and incineration. Many Dutch municipalities had their own landfills, and others shared sites with neighboring communities; about three-quarters of all solid waste wound up in these dumps. Ten incinerators reduced the nation’s urban waste via combustion. In general, the waste sector was dominated by municipalities and local or regional authorities. Standards for air and water pollution were generally low, and little effort was made to purify industrial emissions. At the time, manure was not even perceived as a waste product.

Among the first signs of changing attitudes toward the “inevitable companions of industrial progress” was growing local concern about pol-

1. Jan Bieleman, “Landbouw,” and Ernst Homburg, “Chemie,” in *Techniek in Nederland in de twintigste eeuw*, vol. 2, ed. Johan Schot et al. (Zutphen, 2000), 11–234 and 269–408; Jan Luiten van Zanden, *The Economic History of the Netherlands* (New York, 1997).

2. The Netherlands is nine times smaller than Germany, for example, with a population density of 372 people per square kilometer, in contrast to Germany’s 228 per square kilometer.

lution. More radical environmental groups emerged, distinguished from earlier environmentalists and conservationists by their emphasis on recruiting scientific expertise, organizing protest actions, and seeking media attention.<sup>3</sup> The older, consensus-oriented environmental organizations regularly worked with authorities and policy makers; the new ones rejected that approach, and their attitude reflected broader social changes in the Netherlands. Until the mid-1960s Dutch society was self-consciously organized around religious or political groupings, or “pillars”—Catholics, Protestants, Socialists, Liberals. Each pillar formed a coherent social whole, complete with its own social institutions: political party, schools, unions, broadcasting organizations, athletic clubs, and so on. But in the 1960s this structure crumbled, and Dutch social life became atomized. Radical groups—feminists, students, environmentalists—attacked the existing social institutions and the authorities representing them.<sup>4</sup>

The new generation of environmentalists succeeded in putting issues such as conservation and pollution on the national political agenda.<sup>5</sup> Their success prompted older organizations to become more active, and, after a few contentious years, the Dutch environmentalist community united in the Foundation for Environment and Nature in 1972.<sup>6</sup>

Increasing social pressure and mounting evidence of pollution’s ill

3. These groups confronted chemical factories in particular over their negative effects on the environment. The Society against Air Pollution was founded by activists in the Rijnmond area (the Rhine estuary, near Rotterdam) in 1963. A group named Progil successfully opposed the establishment of a new petrochemical plant near Amsterdam. Progil in particular was characteristic of a new environmental movement emerging in the late 1960s; it recruited scientists to counter arguments advanced by the scientific establishment and mobilized people for actions ranging from protest meetings to distributing posters and leaflets describing potential dangers (explosions, stench) to planting weeping willows in the vicinity of the planned factory, all of which succeeded in drawing the attention of the mass media. See Jacqoline Cramer, *De groene golf: Geschiedenis en toekomst van de milieubeweging* (Utrecht, 1989), 30.

4. Several works explore these structural changes in Dutch society. Sociologists have emphasized the importance of the baby boom generation; see Henk Becker, *Generaties en hun kansen* (Amsterdam, 1992). Becker’s work builds on Ronald Inglehart, *The Silent Revolution* (Princeton, 1977), and Ivan Gadourek, *Social Change as Redefinition of Roles* (Assen, 1982); the generation thesis is further elaborated in Hans Righart, *De eendeloze jaren zestig: Geschiedenis van een generatieconflict* (Amsterdam, 1995). Others dispute the emphasis on the 1960s and trace the roots of change instead to the preceding decade; see Paul Luykx and Pim Slot, *Een stille revolutie? Cultuur en mentaliteit in de lange jaren vijftig* (Hilversum, 1997).

5. For an overview of Dutch opinion and practice regarding nature conservation, see Henny van der Windt, *En dan wat is natuur nog in dit land: Natuurbescherming in Nederland 1880–1990* (Amsterdam, 1995).

6. On the Dutch environmental movement, see Egbert Tellegen and Jaap Willems, *Milieu-aktie in Nederland* (Amsterdam, 1978). On environmental debates in the Netherlands, see Maarten A. Hajer, *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process* (Oxford, 1995), chap. 5.

effects on public health prompted the government to introduce new environmental legislation. A law protecting surface waters was enacted in November 1969, followed by a portfolio of new laws in the 1970s and 1980s.<sup>7</sup> Particularly strict regulations for dumping waste were introduced in 1980 and 1985, and for waste incinerator emissions in 1985 and 1989, both provoked by scandals. In the first case, it was discovered that a new urban development at Lekkerkerk had been built on soil highly contaminated with toluene and benzene. Under public pressure, the entire residential area was demolished and the soil removed. Total redevelopment costs amounted to over two hundred million guilders, about seventy-five million dollars. A number of other former landfills and old industrial sites were subsequently determined to be highly polluted, and remediation costs were estimated at several hundred billion guilders. In the second case, waste incinerator emissions were found to contain alarmingly high levels of dioxin, an extremely toxic substance. In reaction the government introduced the strictest emissions regulations in the world, and many incinerators were closed or completely renovated.<sup>8</sup>

Along with the legislative context, general perceptions of waste and waste treatment began to change, resulting in a new philosophy of waste management. A 1979 parliamentary debate is indicative. The legislators broadly agreed that the best way to handle waste was to prevent it; the next best was to reuse waste products. Ad Lansink translated this agreement into an ordered array of options, in which prevention ranked at the top and dumping ranked at the bottom, and Parliament formally adopted his formulation. In the following decades “Lansink’s Ladder” provided a guideline for handling waste. Dutch policy in this era can be thought of as an effort to climb this ladder—voluntarily or, if necessary, by compulsion.<sup>9</sup>

7. Ministerie van VROM, *Voor-ontwerp van het beleidskader van het landelijk afval-beheersplan* (The Hague, 2001); Afval Overleg Orgaan, *De afvalmarkt: Structuur en ontwikkelingen* (Utrecht, 2000). In 1976, the *Wet Chemische Afvalstoffen* (governing chemical waste products) was passed (Stb, 1976, 214), followed in 1977 by the *Afvalstoffenwet*, a general law regulating waste products (Stb, 1977, 425).

8. Dutch regulations were very strict in comparison to those of other European countries; they were also implemented earlier. The European Union established guidelines for waste incinerator emissions in 1989, while regulations for landfill sites remained an important issue on the political agenda of the European Commission throughout the 1990s. See John McCormick, *Environmental Policy in the European Union* (New York, 2001).

9. This general idea of a ranking of options formed the basis for the waste treatment policy component of a national environmental plan (the *Nationaal Milieubeleidsplan*) in 1989. In support of this policy the government established a national program for research into waste reuse (the *Nationaal Onderzoeksprogramma Hergebruik van Afvalstoffen*, NOH), which fit within the existing framework of national energy research programs set up in response to the first energy crisis. Early on the NOH concentrated on improvements in waste management at the end of the production chain, but later the focus shifted toward prevention and reuse.

As the national government became more involved in waste issues, waste management policy and regulation came largely under its control. Lower levels of government now only executed policy; licenses, inspections, and planning and coordination of waste management processes fell within the provinces' purview, while waste collection and transport remained municipal tasks.

This situation began to change in the 1990s, as the purview of the European Union widened and liberalization created a bigger role for private companies in waste management and waste processing. Emissions standards became increasingly demanding, and some very expensive pollution-reducing technologies were mandated. Among the consequences of these developments was the concentration of waste treatment in fewer and larger facilities.<sup>10</sup>

The high energy prices of the 1970s and early 1980s lent support to arguments in favor of producing energy from waste. When prices started to drop in the mid-1980s, interest in waste-to-energy initiatives declined, only to rebound at the end of the decade as concerns mounted about climate change caused by greenhouse gas emissions. The Dutch government eventually came to regard energy from waste as an important alternative energy strategy, classifying several waste flows as renewable energy sources and subsidizing waste-to-energy projects.<sup>11</sup> Meanwhile, European integration and liberalization of energy markets were creating a new group of actors, private and semiprivate energy companies. These energy distribution companies were looking for market share, unlike the public utilities that had monopolized the energy sector, and sought to gain control over the waste sector.

In short, the perception and administration of waste and waste treatment gradually changed in the Netherlands after the 1960s. Growing environmental awareness spawned new laws and regulations; concentration of treatment and increased scale of facilities altered the overall structure of the waste sector and increased the power of national and provincial governments; and economic pressures spurred attention to the possibilities of waste as a source of renewable energy.

10. The shift in political and administrative control and the trend toward increasing scale provoked organizational changes. The government established a consultative body for waste management (Afval Overleg Orgaan) in 1990, while the waste industry organized itself a year later into the Vereniging Voor Afval Verwerkers (VVAV).

11. This broadening of the concept of sustainable energy was not uncontested, but rather provoked a national debate in which the environmental movement, waste treatment companies, and the government all played important roles. Waste as a sustainable energy source also became a topic of discussion at the European Union level, mainly because the Dutch government succeeded in including organic waste in the European definition of sustainable energy. Rob Raven and Geert Verbong, "Biomassa," in *Een kwestie van lange adem: De geschiedenis van duurzame energie in Nederland*, ed. Geert Verbong (Boxtel, 2001), chap. 8.

It was in this context that researchers and industries sought to develop technologies to reduce the environmental burden created by postwar expansion. In what follows we will trace the process by which three such technologies—for industrial wastewater purification, manure digestion, and the extraction and utilization of biogas from landfills—became embedded in Dutch society. All three were based on the same biochemical foundation, microbes producing biogas (a mixture of methane and carbon dioxide) from organic material in an oxygen-free (anaerobic) environment, but the introductory phase differed for each, and some developments were specific to the Netherlands. Their combined story is particularly interesting because policy makers, researchers, and users conferred special social value on the common element, biogas, which can be used as a substitute for natural gas or directly combusted to produce electricity and heat. Its potential as an alternative energy source constituted an important incentive for all three technologies, linking them to their social context.

Regulatory and economic changes in the Netherlands defined the available “space” for technological experiments and development. We will introduce the concept of a “waste regime” to refer to the regulatory-economic context, and our three case studies will focus on the interaction between the waste regime and technological innovation.<sup>12</sup> We will also distinguish between changes in the waste regime and developments outside it, upon which actors experimenting with new technologies had no influence. Thus,

12. The concept of a waste regime derives from sociological and historical works on technology. Arie Rip and Rene Kemp define a technological regime as “the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures.” This is a reinterpretation of the idea of the technological regime put forward by Richard R. Nelson and Sidney G. Winter, who use the term to refer to a cognitive framework, embedded in the minds of engineers. Rip and Kemp argue that a technological regime is the outcome of the coevolution of the technological, economic, and societal elements. This differs from both Nelson and Winter’s conceptualization of technological development through regimes and Giovanni Dosi’s of development through paradigms, because a technological regime not only exists in the cognitive heuristics or guidelines of designers but is embedded in legislation, dominant technological practices, and institutions. It is a coevolutionary approach because elements in the technological regime develop together and interact with the development of new technologies. See Arie Rip and Rene Kemp, “Technological Change,” in *Human Choice and Climate Change—Resources and Technology*, ed. Steve Rayner and Elizabeth L. Malone (Columbus, Ohio, 1998), chap. 6; Arie Rip, “Introduction of New Technology: Making Use of Recent Insights from Sociology and Economics of Technology,” *Technology Analysis and Strategic Management* 7, no. 4 (1995): 417–31; Remco Hoogma et al., *Experimenting for Sustainable Transport* (London, 2002); Rene Kemp, Peter Mulder, and Carl H. Reschke, *Evolutionary Theorising on Technological Change and Sustainable Development* (Maastricht, 1999); Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, 1982), chap. 11; Giovanni Dosi, “Technological Paradigms and Technological Trajectories,” *Research Policy* 11 (1982): 147–62.

for example, fluctuations in energy prices influenced the waste regime and the possibilities for new technologies throughout the last three decades, but such fluctuations lay outside the actors' spheres of influence and so can only partly explain the course of events. An analytical distinction between the interaction of the waste regime and technological development, on the one hand, and the influence of outside factors, on the other, underscores the complexity of the process of technology introduction.

## The Upflow Anaerobic Sludge Blanket Reactor

In the mid-1980s, sewage treatment plants in the Netherlands processed almost all household wastewater aerobically; anaerobic digestion was then used to reduce odor and kill off pathogens in the thick sludge that remained after aerobic purification.<sup>13</sup> The by-product, methane, was not used, and indeed was often seen as a nuisance.

The use of anaerobic processes in water purification plants has a long history.<sup>14</sup> The first experiment with anaerobic industrial wastewater treatment in the Netherlands took place in 1914 and involved treating the wastewater itself, not the sludge left by aerobic treatment (as in domestic wastewater treatment).<sup>15</sup> Although the experimental facility, at a straw-processing factory, produced technically satisfying results, economic circumstances soon forced it to close. Other countries undertook similar projects. In 1924 a pilot plant was built at a German paper mill, but the technology was not introduced on a larger scale.<sup>16</sup> In 1926, in the United States, the Illinois State Water Survey Division inaugurated a long-term research program; it would eventually contribute substantially to the store of knowledge about anaerobic purification technology, but the project did not build a treatment plant until 1936.<sup>17</sup> In 1937 three plants using anaerobic processes to purify yeast waste were in operation in Denmark and Sweden, and beginning in the 1950s several other countries developed their own test systems.<sup>18</sup>

But the experimental phase was drawn out; commercial plants only

13. In 1965 there were 275 sewage treatment plants in the Netherlands; by the mid-1980s that number had almost doubled. Jan Luiten van Zanden and Wybren Versteegen, *Groene geschiedenis van Nederland* (Utrecht, 1993).

14. Sewage treatment plants started to use anaerobic processes early in the twentieth century. In succeeding decades anaerobic sewage treatment technology improved greatly, particularly in England and Germany, then later in the United States as well. See J. van Brakel, *The Ignis Fatuus of Biogas* (Delft, 1980).

15. Erwin Vermeij, *Contextuele verschillen in de ontwikkeling van technische toepassingen van methaangisting* (Eindhoven, 1990).

16. Brakel.

17. Vermeij.

18. Brakel.



began to be built in the 1970s.<sup>19</sup> One of the first successful anaerobic reactors for processing industrial wastewater was developed in the Netherlands by Gatze Lettinga, a researcher in the Department of Microbiology and Water Treatment at Wageningen University, the center of agricultural research in the Netherlands.

Lettinga began work on the problem in 1970.<sup>20</sup> In contemporary anaerobic reactor designs, wastewater had to remain in the reactor for long periods to ensure adequate purification. When a batch of treated wastewater was removed from the reactor the microbes went with it, for the most part, and the process had to begin again, starting with the growth of a new population of microbes. Because of the long residence time, a large reactor was required to treat a large amount of wastewater. If the microbes could be kept in the reactor, new microbe growth would be less essential and processing time reduced. Lettinga tried to achieve this by fixing the microbes to sand particles and installing a filter that permitted water to flow through the reactor but trapped the particles and microbes. He published a report on this “fluidized-bed system” in 1975, but was rebuffed when he approached a potato starch company about building a test facility.<sup>21</sup>

Lettinga did find a partner a year later, the Centrale Suiker Maatschappij, one of the largest beet-sugar processing companies in the Netherlands. By that time he had refined his design further. Filter obstruction was a problem in the fluidized-bed systems, but Lettinga found that he could eliminate filters completely by sticking the microbes together and sinking them to the bottom. Moreover, the resulting blanket of sludge appeared to have strong purifying characteristics. In the new “Upflow Anaerobic Sludge Blanket” (UASB) design, wastewater flowed from the bottom upward, through the blanket, and methane was extracted at the top. The system was able to purify large amounts of wastewater and collect methane with a fairly small reactor.

By the mid-1970s polluted surface waters were understood to be a serious problem, one aggravated by the fact that many rivers cross or constitute international borders. The Rhine, navigable from Basel to Rotterdam, transported huge quantities of toxic effluents from the Ruhr Valley in Germany to the North Sea.<sup>22</sup> The Dutch began to protest polluting indus-

19. Vermeij.

20. Jaap van de Woestijne, “Anaerobe zuivering heeft de toekomst,” *Beta* 17, no. 9 (14 April 1981). Wim M. Wiegant, “De anaerobe zuivering van afvalwater,” *Biotechnologie in Nederland* 2 (1987): 76–78.

21. Woestijne.

22. Increasing awareness of the problem spurred international cooperation in efforts to reduce and control river pollution from 1970 onward, and agreements between Germany, France, and the Netherlands regulated a variety of polluting substances. See John Robert McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (London, 2000); Flok G. de Ruiter, *In het milieu* (Amsterdam, 1990).

tries in the 1960s, and in 1970 opinion polls indicated that nearly the entire Dutch population (96.2 percent) felt that the government should take action.<sup>23</sup> As has already been noted, one of the first Dutch environmental laws protected surface waters. Among other things, the law used tax policy to reduce untreated wastewater discharges; within a few years of its passage, draining wastewater into open water became very expensive, which spurred industry to find alternative approaches.<sup>24</sup>

The financial incentive created by the new law helps to explain industry's interest in new wastewater treatment technologies. And while aerobic digestion consumes electricity (to pump oxygen), anaerobic digestion produces a usable fuel, which made it especially attractive economically in the 1970s and early 1980s, when energy prices shot up. The network of institutions involved in UASB reactor research expanded to include the University of Amsterdam, the Delft University of Technology, and the National Institute for Public Health and the Environment.

Because the anaerobic process better suits wastewater containing higher proportions of organic material, the first reactors were constructed by firms processing agricultural products, such as sugar beets, but others soon followed.<sup>25</sup> In 1977 the Centrale Aardappelbedrijven, a potato-processing firm, began to test the same reactor design that had been installed by the Centrale Suiker Maatschappij, with promising results that in turn attracted the interest of several other potato processors.<sup>26</sup> Aviko, a producer of potato products, was the next company to install a UASB reactor; it was followed by M. F. F. Kruidingen, a producer of french fries and mashed potatoes, in 1984. In all, ten anaerobic reactors were built by the potato-processing industry in the 1980s, which together treated almost half the wastewater produced by that industry in the Netherlands.<sup>27</sup>

Other sectors followed this lead, including the paper and brewing industries.<sup>28</sup> Roermond Paper built a 1,000-cubic-meter-capacity reactor in 1982, and in 1985 a joint venture involving three paper companies, Industriewater B.V., built a 2,200-cubic-meter reactor that processed between 400 and 800 cubic meters of wastewater per hour. The methane produced by the reactor powered a generator that allowed this venture to become self-supporting in terms of energy. In the mid-1980s Bavaria and

23. Cramer (n. 3 above).

24. Wet Verontreiniging Oppervlaktewateren (Stb, 1969, 526).

25. Klaas Visscher and W. van Starckenburg, "Anaerobe zuivering: Ontwikkelingen en onderzoek in Nederland," *Biotechnologie in Nederland 2* (1987): 73–75.

26. Jaap W. Voetberg, "Anaerobe zuivering in de aardappelverwerkende industrie," *Biotechnologie in Nederland 2* (1987): 79–81.

27. Voetberg; S. Nederhorst, W. van Starckenburg, and Klaas Visscher, *Toepassing anaerobe afvalwaterzuivering: Een inventaristatie van de stand van zaken* (The Hague, 1986).

28. P. J. F. M. Hack, "Anaerobe waterzuivering steeds breder toepasbaar," *Biotechnologie in Nederland 2* (1987): 87–89.

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Grolsch, two large Dutch brewers, introduced UASB reactors in their plants.<sup>29</sup> Brewery wastewater contains less organic material than wastewater from the food-processing and paper industries, but both installations were successful, demonstrating the design's adaptability. The UASB reactors were also significantly less expensive to build than comparable aerobic purification plants.

As its use spread, the UASB reactor design continued to be refined.<sup>30</sup> The main development was adjusting the reactor to different types of wastewater streams, but users also gained experience in optimizing reactor dimensions and understanding operational requirements. A clear pattern emerged: as soon as pilot installations in a new industrial sector showed positive results, other companies followed the initial innovating firm, making only minor refinements. This diffusion process opened a series of new markets for the companies selling this technology.<sup>31</sup>

In 1985 a committee of experts drawn from industry, research institutes, and government concluded that anaerobic treatment was a valuable technology for industrial wastewater carrying easily decomposed organic material.<sup>32</sup> By then about thirty anaerobic reactors had been built, in several countries (table 1). With the exception of one fluidized-bed system at Gist Brocades (a biotechnology company that produced yeast), all were UASB reactors.

Anaerobic treatment of domestic wastewater, which is more diluted and cooler than industrial wastewater, posed more difficult technical problems, which raised a barrier to the adoption of anaerobic digestion as the main purification technology in sewage treatment plants. Nevertheless, UASB reactors continued to spread into the 1990s. To date over a thousand have been built worldwide, and 65 percent of all anaerobic reactors are UASB reactors.<sup>33</sup>

What made the UASB reactor a successful innovation? Technologically, Lettinga solved a key design problem: how to keep the microbes in the reactor as long as possible. More important, the UASB reactor meshed neatly with changes in the waste regime during the 1970s. Growing environmental awareness resulted in new legislation protecting surface waters, which pressured polluting industries and created incentives for them to explore

29. Hack.

30. Nederhorst, Starckenburg, and Visscher.

31. The basic knowledge about anaerobic digestion and the UASB reactor was freely accessible to companies interested in producing parts of the reactor, and several new firms emerged from the early intensive cooperation between industry and research institutes. Companies such as Biothane and Biopaq patented partial improvements to the reactor and have become leaders in this field.

32. Nederhorst, Starckenburg, and Visscher.

33. M. Heselmans, "Oude rot; Milieutechnoloog Lettinga wil kleinschalige waterzuivering," *NRC Handelsblad*, 2 December 2000, 55.

**TABLE 1**  
 UPFLOW ANAEROBIC SLUDGE BLANKET REACTORS IN USE, JULY 1984

<i>Type of wastewater</i>	<i>Country</i>	<i>Number</i>
Beet sugar	Netherlands	7
	Germany	2
	Austria	1
Liquid sugar	Netherlands	1
Potato processing	Netherlands	8
	USA	1
	Switzerland	1
Potato starch	Netherlands	2
	USA	1
Corn starch	Netherlands	1
Wheat starch	Netherlands	1
	Ireland	1
	Austria	1
Alcohol	Netherlands	1
	Germany	1
Yeast	USA	1
Brewery	Netherlands	1
	USA	1
Crustaceans	Netherlands	1
Abattoir	Netherlands	1
Dairy products	Canada	1
Paper	Netherlands	2
Preserved food	Netherlands	1
Alcohol production	Thailand	12
Total		51
Total (Netherlands)		27

*Source*—S. Nederhorst, W. van Starckenburg, and K. Visscher, *Toepassing anaerobe afvalwaterzuivering: Een inventarisatie van de stand van zaken* (The Hague, 1986).

new methods of wastewater disposal. As the number of pilot plants grew, basic knowledge about anaerobic purification and UASB reactors became increasingly widespread. Meanwhile, government subsidies fostered research and development.<sup>34</sup> Finally, the 1973 energy crisis stimulated energy-saving projects, which was especially important in the experimental phase and allowed the technology to mature. By the time energy prices fell,

34. Nederhorst, Starckenburg, and Visscher (n. 27 above).

the anaerobic digestion of industrial wastewater was an established purification method.

### Anaerobic Manure Digestion

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In the late 1970s and early 1980s, anaerobic manure digestion seemed a promising method of producing energy on farms throughout Europe. That promise was borne out in countries such as Denmark and Germany, but in the Netherlands it failed within a few years.<sup>35</sup>

Lood van Velsen, a graduate student of Lettinga's at Wageningen University, started work on anaerobic manure digestion in 1975. His research at first focused simply on reducing odor, but rising energy prices and growing interest in alternative energy sources quickly led him to concentrate on biogas production. Estimates in the early 1980s indicated that Dutch farms could produce the biogas equivalent of about 800 million cubic meters of natural gas, or roughly 1 percent of total gas production in the Netherlands.<sup>36</sup>

Van Velsen and Lettinga constructed the first Dutch manure digester on a pig farm in Gardingen in 1979. Farmers saw a potentially large energy source right in their own yards, and engineers and scientists envisioned a large market.<sup>37</sup> Against this background, Van Velsen and Lettinga initiated a follow-up research program focused on cattle farms, the aim of which was to develop technically and economically feasible biogas plants.<sup>38</sup> The

35. Denmark had fifty anaerobic manure digestion facilities in 2001, while in Germany the number exceeded fifteen hundred. The total number of plants can give a distorted view of installed processing capacity, as they vary in size. In Denmark, twenty of the fifty plants were centralized biogas facilities in which up to one hundred farmers cooperated; the remaining thirty were single-farm facilities (some very large). In 2001, total annual energy production from all fifty Danish plants was about 1.3 petajoules. In Germany, almost all anaerobic manure digesters were small-scale, single-farm facilities; total annual energy production by these facilities was about 3.7 petajoules in 2001. See Jens B. Holm-Nielsen and Teodorita A. Seadi, "State of the Art of Biogas in Europe," and C. da Costa Gomez, "State-of-Art and Future Development in German Biogas," in *Bio Energy 2001—Nordic and European Bioenergy Conference Proceedings*, ed. Teodorita A. Seadi, G. Kirsten, and Jens B. Holm-Nielsen (Esbjerg, 2001), 44–50 and 126–34; T. A. Seadi, *Danish Centralised Biogas Plants* (Esbjerg, 2000); O. Elmoose, *Gårdbiogas* (2002).

36. P. A. de Boks and Wim J. van Nes, *De haalbaarheid van een rendabele biogastallatie voor de middelgrote melkveehouderij* (Delft, 1983); Centraal Bureau voor de Statistiek, *1899–1994 vijftienennegentig jaren statistiek in tijdreeksen* (The Hague, 1994).

37. Samenwerkende Electriciteits Producenten, *Elektriciteit in Nederland* (Arnhem, 1982).

38. K. W. van der Hoek, *Methaangaswinning en -benutting op melkveebedrijven* (Wageningen, 1984). One of the reasons for shifting their attention to digestion of cattle manure was that van Velsen already knew a lot about digestion of pig manure. P. Hoeksma and H. Arkenhout, *Bouw en toetsing van een installatie voor biogaswinning in combinatie met een gasmotor-generator op een melkveebedrijf* (Wageningen, 1984).

budget for this relatively small program, which ran from 1980 to 1983, was 2.8 million Dutch guilders, about one million U.S. dollars; 60 percent of it came from the Ministry of Economic Affairs, which had responsibility for energy research.<sup>39</sup> Researchers from Wageningen University's departments of microbiology and water treatment cooperated with others from the Instituut voor Mechanisatie, Arbeid en Gebouwen (Institute for Mechanization, Labor and Buildings) and the Instituut voor Wegtransport Middelen (Institute for Road Transport Means) in the project.

The researchers' main task was to improve microbiological conditions for biogas production. They built a test facility on a cattle farm in Duiven, near Wageningen, similar to the one that Van Velsen and Lettinga had built in Gardingen, but larger. Cattle manure differs somewhat in composition from pig manure, and the researchers expected anaerobic digestion to work better with that material. The original plant design used a monopump, which cut up the manure and supplied it to the digester. A heat exchanger kept the digester at thirty degrees Celsius, and a blower recirculated biogas to the digester to mix the manure. The biogas produced was stored in tanks, to be transported to a gas engine and combusted.<sup>40</sup>

The researchers began work with only a meager knowledge base. The small pilot plant in Gardingen was the only anaerobic manure digester in the Netherlands. Others did exist elsewhere—in England and Denmark—but information about them was limited.<sup>41</sup> The engineers and farmers involved in the project had to learn by doing. Problems arose with the monopump and the heat exchanger, and the high sulfur content of the biogas caused corrosion in the gas engine. At the end of the program, the researchers concluded that manure digestion, though technologically feasible, would have to be scaled up to become economically feasible; larger-scale operations would mean less work for individual farmers, lower production costs, and a better balance between energy produced and energy demanded.

By 1983 the number of new digesters reached twenty-five, and anaerobic manure digestion may have been close to a commercial breakthrough at that point. But increased numbers could not conceal troubles within the projects. An inquiry among seventeen plants revealed numerous technical problems.<sup>42</sup> New estimates showed that only about a thousand farms in the Netherlands produced enough manure to process cost effectively. Nevertheless, the researchers remained upbeat. They argued that manure digestion was a new technology and that the obstacles encountered in its early stages were only to be expected, and could be overcome.<sup>43</sup>

39. Hoeksma and Arkenhout.

40. Hoek.

41. Hoeksma and Arkenhout.

42. Boks and Nes (n. 36 above).

43. On the basis of such hopes, the Centrum voor Energiebesparing (Center for

Though researchers did succeed in overcoming various technical challenges, in the late 1980s their efforts came to an abrupt end as the steep drop in energy prices made producing biogas from manure economically unattractive. Most renewable energy technologies endured similar setbacks during this period, but anaerobic manure digestion faced others as well. Memories of difficulties encountered in the early 1980s discouraged manufacturers and users.<sup>44</sup> Individual farmers could not afford the time and effort for maintenance and repairs. Most important, growing concern about manure surpluses in the Netherlands became a decisive barrier. This was a remarkable development; in the mid-nineteenth century, one of agriculture's main problems had been a shortage of fertilizer. The situation changed dramatically over the course of the next century, and intensive use of chemical fertilizers made possible enormous leaps in agricultural productivity.<sup>45</sup> In the Netherlands, an excellent academic and financial infrastructure supported these developments, resulting in a highly competitive and specialized sector.<sup>46</sup> Decreasing acreage under production and increased specialization produced a new form of agricultural industry. In particular, the numbers of cows, pigs, and chickens rose dramatically.<sup>47</sup> These animals were concentrated in a few regions, with pigs and chickens packed in sheds resembling factories—hence the name coined for this type of agriculture, “bio-industry.”<sup>48</sup> Although immensely profitable, bio-industry failed from an environmental point of view. More even than the air and

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Energy Saving), an organization that consults on alternative energy sources, set up a digestion facility on an experimental farm in Assendelft, in the northern Netherlands, working in cooperation with Oostwouder Inc. and Genap, two manufacturers of biogas installations, within the framework of the Nationaal Onderzoeksprogramma voor Hergebruik van Afvalstoffen. The experimental digester combined the production and gas storage tanks, which substantially reduced investment costs. The disadvantage was that plant operations became more complex, which increased maintenance work. Despite the best efforts of all involved, the experiment produced disappointing results—persistent technical problems and bleak economic prospects. See Wim van Nes, *De ontwikkeling van een goedkopere mestvergistingsinstallatie voor de middelgrote melkveehouderij* (Delft, 1987).

44. Raven and Verbong (n. 11 above).

45. McNeill (n. 22 above) argues that chemical fertilizers and irrigation beyond the immediate confines of river valleys permitted Europe (after 1920) and the United States (after 1930) to forgo net cropland expansion; by the 1960s almost all efforts to expand food production in Europe and North America focused on obtaining more harvest per acre rather than on farming more acres. The Green Revolution brought this trend to the Third World by introducing high-yield hybrids from the International Rice Research Institute. One of the disadvantages of these developments, however, was that the high yields depended on heavy, and increasing, use of chemical fertilizers. See Ken A. Gourlay, *World of Waste* (London, 1992).

46. Bieleman (n. 1 above).

47. In 1990 there were almost one hundred million chickens and fourteen million pigs in the Netherlands—about as many pigs as human inhabitants.

48. Zanden and Verstegen (n. 13 above).

water pollution it created or the concerns it raised about the inhumane treatment of animals, the massive amounts of manure produced by bio-industry posed a problem.<sup>49</sup>

For a time a powerful “Groen Front”—a network of farmers, farmer organizations, agricultural industries, and the Ministry of Agriculture—succeeded in concealing the problems being created by the bio-industry from the public, but a clearer picture gradually emerged. In 1984 the national government declared a temporary moratorium on new farms, and in 1987 enacted a law to deal with farming and animal waste.<sup>50</sup> This legislation, which, predictably, met with resistance from farmers, mandated radical changes. It set strict requirements for establishing new farms, obliged farmers to keep track of manure production, and imposed fines for manure surpluses.<sup>51</sup>

Such developments had a decisive effect on anaerobic manure digestion technology. One reason Dutch farmers were reluctant to adopt the technology was its relatively low biogas yield. Codigestion—that is, the digestion of manure together with other organic materials—produced higher yields in Germany and Denmark. But codigestion was blocked in the Netherlands because manure was included within the waste regime, and strict regulations controlled the amount of copper and zinc that farmers could spread on their land. Adding other organics to manure was not feasible because farmers did not know the precise composition of these materials and the amounts of copper and zinc they contained could vary. Moreover, the Ministry of Agriculture’s general policy was to remove nutrients (especially nitrogen) from the manure surplus (either by exporting the waste products or by combustion). The digestion process does not decrease the amount of nutrients, and codigestion increases it, so neither fit the ministry’s general policy.

Research therefore shifted from biogas production on individual farms to large-scale manure processing and export of minerals, and the focus shifted to waste management as opposed to energy production. These new efforts failed in the 1990s, mainly for lack of a market for the products and lack of cooperation from farmers, who had to pay more to have their manure processed in the plant than to transport it unprocessed to farmland elsewhere.

49. Though manure has, of course, always been an essential resource for farmers, extensive reliance on chemical fertilizers has made it much less important, and in any case the amount of manure produced by industrial farms greatly exceeds the farmers’ ability to use it as fertilizer.

50. *Meststoffenwet* (Stb, 1986, 598).

51. At first the law had exactly the opposite of its intended effect. Because it prohibited the expansion of livestock farming, many farmers increased production before it took effect, and even after it did the number of animals continued to increase for a few years, because of applications submitted prior to enactment. See Zanden and Versteegen.



The failure of anaerobic manure digestion in the Netherlands cannot be traced to intrinsic characteristics of the technology. A comparison with countries such as Denmark and Germany shows that the existing waste regime plays a crucial role, while timing is also important. The inclusion of manure in the waste regime came at a rather unfortunate time in the Netherlands. Regulations grew more restrictive as the severity of the problems associated with industrial agriculture became more evident. Research into anaerobic manure digestion did not revive until the late 1990s.<sup>52</sup>

### Biogas from Landfills

The years from 1970 to 2000 also saw the development in the Netherlands of a third waste management technology based on anaerobic processes, biogas extraction from landfills. Dumping was the traditional solution for domestic and industrial waste, but it became a problem in the twentieth century as the amount of waste increased dramatically and it became more toxic. Little attention was paid to this burgeoning source of pollution before the 1970s. The notorious Love Canal near Buffalo, New York, symbolizes toxic waste dumping in the industrialized world, but Western Europe soon added its own scandals, including the 1980 Lekkerkerk incident in the Netherlands, mentioned above.<sup>53</sup> There were thousands of polluted areas across the industrialized world, and remediation costs mounted into the billions of dollars.

It was against this turbulent background that experiments with extracting gas from landfills began, spurred by a number of factors. Digestion of organic material such as domestic waste within a landfill takes place in a naturally occurring anaerobic environment. During the period of high energy prices in the late 1970s and early 1980s, the methane by-product of this “natural” anaerobic process began to look like a resource to be exploited, all the more so as landfills grew larger. Moreover, uncaptured methane killed vegetation near landfill sites and created a danger of fires and explosions.<sup>54</sup>

52. The renewed interest was due to increasing concern over climate change and national targets for sustainable energy.

53. Hooker Chemical Company dumped more than twenty thousand tons of chemical waste in Love Canal from the 1940s to 1952. The company later sold the site to the local board of education, which built a school there, and a housing development followed shortly after. In 1978, 237 families were forced to leave their homes after cases of cancer and physical deformities in children were linked to the liquid and sludge seeping into the basements of the houses. In the 1980s other Hooker dump sites also appeared to be heavily polluted; Gourlay (n. 45 above).

54. Gas fires and explosions occurred regularly in the United States in the 1940s and 1950s at landfill sites that had been covered to reduce odors. In the literature this development is called the transition from dumping to sanitary landfill sites. H. Lanier Hickman Jr., *A Brief History of Solid Waste Management in the U.S., 1950–2000*, <http://>

The first Dutch experiments with landfill gas extraction were undertaken by the Vuil Afvoer Maatschappij (VAM), a waste disposal company in Wijster. This company, which handled waste from larger cities, controlled the largest landfill site in the Netherlands: more than 100 hectares (250 acres) of land, with the capacity to store about twenty-five million cubic meters of waste.<sup>55</sup> During the 1970s the VAM had introduced an advanced system for separating domestic waste that used three gas-fueled engines to supply electricity and heat. In 1978 the company initiated two related research projects, one an attempt to extract biogas from the landfill, the other investigating ways to reduce damage to the environment. It was joined in these efforts by the public research centers Instituut voor Cultuurtechniek en Waterhuishouding (Institute for Cultural Technology and Water Management) and Instituut voor Afvalstoffenonderzoek (Institute for Waste Research). The results were so promising that the VAM decided to move forward with commercial exploitation.

In 1983 the company completed the first landfill gas extraction system in the Netherlands, built around several kilometers of trenches covered with domestic waste. Gas was extracted from these tunnels and transported to a dryer; from there it went to fuel the three gas engines that provided electricity and heat for the separation system and buildings. (The engines had to be modified to use biogas, which differs somewhat from natural gas in composition.)

Others followed suit. A landfill in Bavel had already started to extract and flare off landfill gas in 1981 as an odor-control measure. In 1984 the Rikkerink landfill in Ambt-Delden set up an extraction system, spurred by the chance to market the gas to a nearby chemical company.<sup>56</sup> In 1985 a landfill in Joure began to sell electricity from biogas-fueled generators to a local energy company.

Landfill gas seemed a promising new energy source. In 1982, researchers calculated that twelve landfill sites could produce 150 million cubic meters of biogas per year for the next twenty-five years in an economically feasible way.<sup>57</sup> A 1985 estimate foresaw potential production of 220 million cubic meters from twenty-six landfills.<sup>58</sup> Such predictions stimulated several new projects in the mid-1980s—and then energy prices began to fall.

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[www.forester.net/msw\\_0101\\_history.html](http://www.forester.net/msw_0101_history.html); J. Hoeks and J. Oosthoek, “Gaswinning uit afvalstortterreinen,” *Gas* 11 (1981): 563–68.

55. J. Oonk, M. J. J. Scheepers, and J. W. Takke, *Overzicht stortgasprojecten in Nederland (1983–1991)* (Apeldoorn, 1993).

56. *Ibid.*

57. This was less than the estimated potential production from manure digestion, but still represented a considerable amount of energy. Algemene Energieraad, *Duurzame energie; Knelpunten bij introductie van duurzame energie* (The Hague, 1982).

58. Rijksinstituut voor Volksgezondheid en Milieu, *Gaswinning uit Nederlandse stortterreinen* (Bilthoven, 1985).

The market value of landfill gas decreased by 60 percent, which hit landfills such as Ambt-Delden and Bavel, where biogas was used for industrial purposes, very hard.<sup>59</sup>

Changes were also occurring at the policy level. Dutch waste policy generally aimed to reduce waste through prevention and recycling; it also called for separate collection and processing of organic domestic waste. This reduced the amount of organic waste going to landfills, which in turn affected biogas production.<sup>60</sup> Viewed from that perspective, landfill gas extraction was a proven technology with a bleak economic future.<sup>61</sup> On the other hand, changes in environmental policy stimulated development. Legislation passed in 1993 required landfills to plant trees and other vegetation to soak up rainwater and keep it from seeping through the waste and polluting groundwater.<sup>62</sup> This mandate inadvertently made gas extraction systems almost necessary for landfills, because trees and plants do not grow well on a methane source. Rising concerns about climate change also made gas extraction seem attractive, for two reasons: methane is a much more important greenhouse gas than carbon dioxide, and capturing landfill emissions kept them from reaching the atmosphere; and using methane as an energy source reduced the consumption of fossil fuels. As the environmental policy context shifted, several landfill sites revived plans for gas extraction systems, and others prepared new initiatives.

Between 1987 and 1991 ten Dutch landfills built gas extraction systems. The biogas produced by these facilities was used in electricity and heat generation, and some was also refined and injected into the natural gas infrastructure.<sup>63</sup> In 1990, eighty-seven landfills were in operation in the Netherlands and fifteen new sites were projected. Almost half of these were unsuited to landfill gas extraction due to limited dumping of organic waste.<sup>64</sup> In 1991, fourteen landfill sites recovered over seventy-three million cubic meters of landfill gas, of which some fifty-one million cubic meters were used (the rest was flared off). Clearly, landfill gas remained a largely unexploited resource.

Acting on that observation, in 1992 the Nederlandse Organisatie voor Energie en Milieu (Netherlands Agency for Energy and the Environment) joined the Vereniging Van Afval Verwerkers (Association of Waste Processors) and EnergieNed (an association of energy distribution companies) to

59. M. J. J. Scheepers, "De toepassing van stortgas in Nederland," *Gas 5* (1991): 200–205.

60. The Netherlands banned the dumping of numerous organic wastes in 1996, while in other European countries discussions on banning such wastes continued throughout the 1990s; McCormick (n. 8 above).

61. Scheepers.

62. Stortbesluit Bodembescherming (Stb, 1993, 55).

63. Oonk, Scheepers, and Takke (n. 56 above).

64. G. J. Kremers, W. F. T. Tromp, and J. W. Takke, *Winning en benutting van stortgas in Nederland* (Deventer, 1990).

establish the Adviescentrum Stortgas (Advisory Landfill Gas Center).<sup>65</sup> The Adviescentrum aimed to double the number of new landfill gas projects; it performed feasibility studies at all landfill sites and arranged a dialogue between landfill owners and energy companies. The latter were increasingly interested because electricity from biogas generation was classified as renewable or “green” electricity in 1996, which made it exempt from a special tax on electricity that had been introduced to promote energy efficiency and renewable energy, and their interest grew as biogas production rose. The Adviescentrum gave advice, published a newsletter, organized meetings, seminars, and workshops, and cooperated with legislation, and these efforts paid off. The number of landfills with gas extraction systems increased from fourteen in 1991 to forty-four in 1997; the amount of landfill gas used for power generation grew 105 million cubic meters in 1994 to 124 million cubic meters in 1996. Its goals achieved, the partner organizations dissolved the Adviescentrum in 1997.

The rapid development of landfill gas extraction is connected to its relevance in the changing waste regime. New legislation, subsidies for waste-to-energy projects, and the increased scale of the waste stream all favored landfill gas extraction. The International Energy Agency still sees great potential for biogas recovery from landfill sites worldwide. In 2000, more than six hundred landfill gas recovery schemes had been implemented, of which the Netherlands accounted for about 10 percent.<sup>66</sup> However, if the general policy of prohibiting dumping of any organic waste in landfills persists, the long-term outlook for this energy source is dim.

## Explaining Success

Why do some environmental technologies succeed while others fail? Biogas production is environmentally and economically attractive, yet the three technologies summarized here have met with significantly different degrees of success. How can we understand these differences?

The influence of context is pronounced. The dynamics of the regulatory and economic framework—the waste regime—are particularly important. Actors involved in technological development have to work within it, which guides and limits their actions. Changes in the regime determine their abil-

65. Adviescentrum Stortgas, *Stortgaswinning en -benutting in Nederland* (Utrecht, 1997).

66. The largest biogas producer is the United States, although production efficiency there is “far below the potential level” of between 20 percent and 40 percent. Sweden scores highest in terms of production efficiency, with a realized potential of 30 percent; the realized potential in the Netherlands was about 20 percent. Improved landfill designs and the development of new landfill technologies, such as biofills, can contribute significantly to increasing the efficiency of landfill gas recovery. See IEA Bioenergy, *International Perspective on Energy Recovery from Landfill Gas* (Harwell, 2000), 1–4.

ity to develop new technologies, opening up some paths while blocking others. But a technological regime does not dictate the actions of the actors involved; researchers, companies, and inventors often pursue new directions or try to optimize the possibilities for a technology they advocate or prevent changes they fear. More general contextual factors—such as oil price conditions or new social movements—also influence outcomes.

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The UASB case illustrates how developments at the regime level can create space for new technological experimentation. Various industrial sectors gradually became interested in the UASB reactor. The main drive was to comply with environmental trends in the waste regime, such as new legislation and rising taxes. Biogas production was simply a bonus. Industry was already somewhat familiar with this type of technology, which put it in a more advantageous position than anaerobic manure digestion. In addition, the scale of industrial waste streams made the UASB reactor more attractive. Ingenuity and perseverance, together with support from a research infrastructure, combined to make the UASB reactor a success.

The same research infrastructure was involved in the development of manure digestion technology, with less success. Farmers were unfamiliar with such technology and proved unwilling to spend much time or effort on it. The classification of manure as a waste product raised a critical barrier. A growing manure surplus and the agricultural sector's refusal to acknowledge this as problem led to fairly strict regulations, which prevented the codigestion of manure with other organics—an important factor in the success of digestion plants elsewhere. Engineers were forced to try to develop large-scale manure-processing technology, but despite massive investment and subsidies by the government they failed in that undertaking—mainly because such technology failed to embed itself in the social context. Energy prices—the high prices of the early 1980s and the low prices after 1986—also exerted important influence.

Anaerobic manure digestion illustrates three important features of new technology. First, the combination of various, often reinforcing, developments is more decisive than any single factor. In this case, changes in environmental legislation and falling energy prices combined to halt experiments in the late 1980s—but in the context of European Union environmental policy harmonization and the growing importance of renewable energy, new prospects for manure digestion technologies exist in the Netherlands. Second, conflicting interests can have important effects. The agricultural lobby, including farmers, vehemently opposed new legislation governing treatment of animal wastes—meaning the inclusion of manure in the waste regime—though ultimately very strict legislation passed. Third, timing is critical. If the experiments had started five or ten years earlier, success would have been much more likely. In hindsight, opposition to interfering with manure cost precious time. Timing is to a high degree a contingency factor;

the rise and fall of oil prices, for example, lies outside the sphere of influence of the actors involved.

Landfill gas extraction demonstrates the dynamics of contextual factors. The technology involved is quite simple and widely understood. It fits neatly into the growing environmental awareness of climate change, illustrating the importance of actors' anticipation of changes in the regime. Some, early on, viewed gas extraction technology as proven but with little economic future, effectively snuffing out initiative; later, after the passage of new environmental laws and the revival of interest in renewable energy, others perceived it as only a short-term option. The same developments that are decisive for short-term success can limit long-term prospects, if conditions do not change dramatically. To use a software analogy, the "uninstall" option is built in.

This article has offered insights into the diffusion of innovative environmental technologies. It also raises another interesting question: how does that diffusion differ from similar processes affecting innovations in production and consumer goods? Can we distinguish patterns and mechanisms specific to environmental technologies? Regulatory and political decisions were of great importance to the diffusion of all three technologies outlined here, probably much more than is the case with consumer products. The landfill gas case offers the best example: regulatory decisions both encouraged diffusion and made it obsolete for the future. The UASB reactor and manure digestion plants were also affected by regulations, either through public incentives or legal interpretation. Regulations and political decisions thus act as important selection criteria in diffusing environmental innovations. Moreover, the capricious nature of such selection criteria may explain the often problematic diffusion of environmental technologies, as it is difficult for technologies to become embedded in a fluid social context.