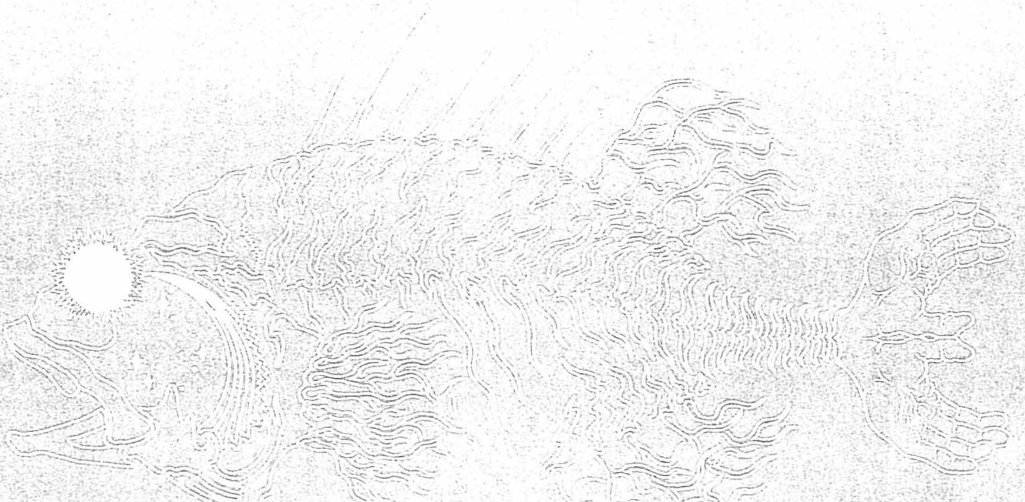


Energy

As the idea of massive, single-shot solutions to energy demands wanes with the increasing unavailability of inexpensive, accessible energy sources, the appeal and the rather satisfying logic of smaller scale, and specific end-use energy applications begins concomitantly to win acceptance. In his article, "An Integrated Wind-Powered System to Pump, Store and Deliver Heat and Cold," Joe Seale discusses first the theoretical aspects and potential pitfalls of such a system and then goes on to some of the practical potential applications. Joe's subsequent shorter article, "Whatever Happened to Compressed Air?" further illustrates from our own recent experiment that, as with the application of any technology still in its infancy, there is still considerable trial and, in this one specific case, error.

Gary Hirshberg's "A Water-Pumping Windmill Primer" is the continuation of a series of hands-on or how-to papers on water-pumping mills that we have published over the years. As both we and our mills become more experienced and durable, we feel very eager to pass on what we have learned. Gary has worked extensively with our own sailwing water-pumper, Big Red, and built a duplicate in Boston for the Boston Urban Gardening program. He has also traveled about visiting other windmill sites and windmill people and has taken courses in building windmills, so it is obvious that his writing springs pretty directly and recently from his own experience.

NJT

As the idea of massive, single-shot solutions to energy demands wanes with the increasing unavailability of inexpensive, accessible energy sources, the appeal and the rather satisfying logic of smaller scale, and specific end-use energy applications begins concomitantly to win acceptance. In his article, "An Integrated Wind-Powered System to Pump, Store and Deliver Heat and Cold," Joe Seale discusses first the theoretical aspects and potential pitfalls of such a system and then goes on to some of the practical potential applications. Joe's subsequent shorter article, "Whatever Happened to Compressed Air?" further illustrates from our own recent experiment that, as with the application of any technology still in its infancy, there is still considerable trial and, in this one specific case, error.

Gary Hirshberg's "A Water-Pumping Windmill Primer" is the continuation of a series of hands-on or how-to papers on water-pumping mills that we have published over the years. As both we and our mills become more experienced and durable, we feel very eager to pass on what we have learned. Gary has worked extensively with our own sailwing water-pumper, Big Red, and built a duplicate in Boston for the Boston Urban Gardening program. He has also traveled about visiting other windmill sites and windmill people and has taken courses in building windmills, so it is obvious that his writing springs pretty directly and recently from his own experience.

NJT

A Water-Pumping Windmill Primer

Gary Hirshberg

Most readers of *The Journal of the New Alchemists* do not need to be lectured on the merits of substituting wind power for conventional energy sources. To a believer, a windmill is more than an alternate energy device. It is a key to independence and self-sufficiency—an inspiration and a banner declaration of new attitudes. It's sexy and lots of fun.

Because most of us alternative-minded folks are already convinced, all we really need is to have our heads pointed in the right direction. As with any new technology, we need a theoretical understanding of the device, an economic perspective on the application, and, perhaps most important, a reasonable and current dose of product knowledge in the appropriate field(s). These foundations having been laid, the requisite information for installing and maintaining a wind system comes easily.

This article attempts to give you some of the foundation in each of these areas. I shall discuss the comparative advantages of water-pumping windmills and look briefly at their use through history. I shall examine the parts of a typical water-pumping windmill system and will discuss how to select a mill for a particular application. Finally, I'll share a few "tricks of the trade" as to erecting and maintaining a mill.

Wind-powered water pumping is dependable. A properly installed and maintained wind-powered pump can give over forty years of reliable service. Recently I dismantled an 1893 Corcoran mill that was still pumping after eighty-six years. A regreasing and the replacement of a few parts has it in shape again for at least another eighty.

Water pumping with wind is cheap, and needless to say, with escalating fuel costs, the relative savings will be increasing over time. In 1973, Prof. Stephen Unger of Columbia University published a note in the *New York Times* in which he analyzed the economics of electric pump vs. windmills. He found that a typical water-pumping windmill costs 50% less than a comparable electrical submersible pump over the lifespan of the mill, which is rated conservatively at twenty years.[1]

As I hope this article will make clear, wind-powered water pumping is easy, requiring about the same skills it takes to perform home plumbing tasks, or to build a small shelter.

And finally, harnessing the wind for your energy needs is inspiring and joyful. The gentle, steady sweep of moving blades and the trickle of water from your well gives a sense of independence, responsibility, and an attunement with Gaia and her delicate richness. For most of us, the transition to a wind-powered water system can be simple and reassuring. For those not yet prepared to separate themselves from conventional power sources, or for those with marginal winds, a number of efficient and low-cost compromises are available.

WINDMILLS VS. WIND GENERATORS

For the windmill neophyte, let's first distinguish windmills from wind generators. Windmills are machines that capture the energy in the winds directly for such mechanical work as water pumping, grinding, compressing air, etc. Wind generation, which involves the transformation of wind energy to electricity can be efficient but is generally more expensive and obviously is more complex.

The current, near-exclusive focus on electrical generation cannot be taken as evidence of the superiority or even the necessity of electricity for all wind energy uses. The energy requirement for pumping water is less than that for electrical generation. Water pumpers are designed to operate in lower winds and at lower power levels than wind generators, and thus are able to operate in a wider range of locations. The lifting and transporting of water is an appropriate use of wind power because it is a direct mechanical application that requires moderate energy inputs. Energy storage is facilitated effectively and cheaply by storing water for windless periods.

A less obvious advantage of direct wind-powered water pumping deserves mention. Should a fire break out in a house or workplace, one of the first items to go is electrical wiring. If that is the power that you are relying on for water, to put it bluntly, your goose is cooked.

A BRIEF HISTORY OF THE WATER-PUMPING WINDMILL

The roots of wind-powered water pumping are noble indeed. The first recorded mills are from seventh-century Persia and were used for grain grinding and irrigation. The first account of windmills in Europe dates from 1105 when a French permit was issued for the construction of a water-pumping machine. A deed from Normandy contains the same report from 1180. The thirteenth century saw windmills gain widespread acceptance. In the fourteenth century, Dutch "scoop" or "tower" mills came into use for grinding corn and pumping water. It is known that there were at one time approximately 9,000 wind machines in Holland, a number so significant that in the early 1600's the Bishop of Holland claimed the wind as his own and imposed an annual duty on windmill owners. (Even the utilities have distinguished roots.) By the late nineteenth century, there were more than 30,000 mills operating in Denmark, Germany, Holland and England producing the equivalent (in mechanical power) of 1 billion kilowatt-hours (kwh) of electricity.[2]

The multibladed American windmill actually bears little relation to the European mills. During the period of the great western thrust of the railroad, steam locomotives needed dependable water supplies particularly in the remote, dry areas. With classic Yankee ingenuity, a man named Daniel Halliday invented the American multibladed mill in 1854. Unlike the inefficient Dutch scoop mill which was incapable of lifting water more than 16 feet, Halliday's mills could draw water from hundreds of feet below the surface. He sold thousands of these large diameter (25 foot) machines. In 1886, Thomas Perry came up with a model for an aerodynamic blade, a design that has not been improved upon even by the most sophisticated computer projections. Perry's model has been in use ever since. The period from 1880 to 1910 saw over 100 manufacturers in the windmill business. Between 1880 and 1900 the combined capital investment in the American windmill industry grew from less than $700,000 to $4.3 million.[3] Since almost all the machines were open-geared, the cowboys on large ranches were sent out each week with oil-filled saddle pouches, or with corked whiskey bottles filled with replacement grease, to keep stock-watering mills in good shape. Most cowboys detested these machines as they did all mechanical devices ("can't eat a windmill when things get rough").

In 1915, the Aermotor Company of Chicago patented the first self-oiling machine which simply enclosed the open gears under a water-resistant case. This early and decisive advantage catapulted Aermotor into being the most widely distributed machine in the history of the business, accounting for 70% of all sales in the 1920's. Windmills continued to boom until the early 1930's when rural electrification promised (deceptively) cheap power to every home and

---

[1] S. Unger, "Disappearing Windmills," Letters to the Editor, *New York Times*, January 3, 1973.

[2] Wilson Clark, 1975, *Energy For Survival*, Garden City, N.Y.: Anchor Books, p. 521.

[3] "Windmills in Foreign Countries." Special Consular Reports, Vol. 31, U.S. Department of Commerce and Labor (Washington, D.C.: Government Printing Office, 1904), p. 17.

farmstead. The electric-pump people must have followed closely behind the electric-line layers, for the windmill business dropped with a subsequent sudden crash. There are still a few hundred thousand mills standing out there, and a fraction of them are still pumping. Now, thanks to skyrocketing energy costs, Three Mile Island, and a general dissatisfaction with helpless dependency on the power grids, water pumpers are starting to sell again around the country and around the world.

THE WATER-PUMPING WINDMILL

Excluding the well and storage facilities, a current water-pumping windmill consists of most of the basic components shown in Figure 1. These are:

The Wheel or Rotor Assembly

The wheel is the part of the machine that catches the energy of the wind and converts it to rotary mechanical power which is available for work. Wheel diameter is a critical factor in determining the appropriate machine for your needs. The diameters of commercially available wheels range from 6 to 16 feet. In some cases 20 foot wheels are available. I shall discuss how to choose the correct diameter in the next section. The power of a wind machine is proportional to the square of the diameter of the blades. If the diameter of the blade is doubled, the power output is therefore quadrupled.

The overall power conversion efficiency of the large surface area water-pumper wheels is much lower than the sleek aerodynamic blades of a high-speed wind generator. Most water pumpers are designed to furl out of the wind at 35 rpm. Such wheels are designed to produce high torque at low wind speeds, however, and therefore are well suited to direct mechanical applications.

The Gear or Transmission

The wheel connects to the gear which converts rotary motion into vertical motion for pumping. Typical gear ratios are 4:1, that is four rotor turns for one pumping stroke. Most modern water pumpers have closed gearboxes and require only an annual oil change.

The Tail (optional)

Windmills can be either upwind or downwind machines. Upwind machines require a tail to keep the nose or wheel into the wind. The disadvantage lies in the cost of extra materials. The advantage of a tail is that it can be triggered by a spring connected to the gearbox to pull parallel to the wheel in high winds. This self-furling mechanism, which can be adjusted by the spring tension, effectively shuts down the mill and prevents self-destruction in high winds. When the gusts subside, the tension on the spring releases, the tail opens out, and the wheel turns back into the wind. We chose a downwind design for our New Alchemy sailwing in spite of this asset, in an effort to develop the lowest-cost water-pumping solution. I don't know of another downwind water pumper on the market today.

The entire top assembly including the wheel, tail, and gearbox are mounted on a turntable or shaft which allows orientation or yaw with changing wind direction.

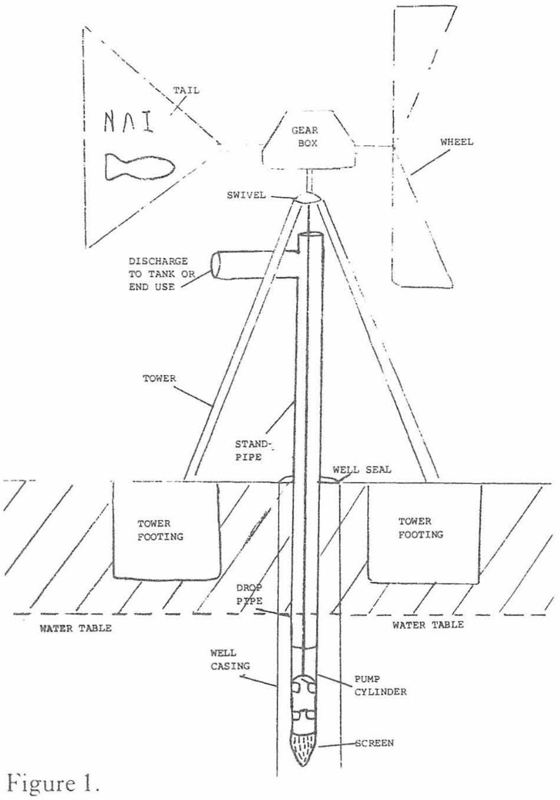


Figure 1.
The Components of a Water-Pumping Windmill.

The Tower

The most important consideration for the tower is to get the wheel above nearby wind obstructions. As a general rule, the tower should be at least ten feet higher than any obstructions to wind flow within 100 yards of the mill. Commercial towers available from water pumper manufacturers range in size from 21 to 47 feet in height. For higher towers, wind generator catalogues should be consulted.

The tower must be absolutely plumb and the tower-top platform level, or the lifetime of the machine will be drastically shortened. Needless to say, the tower must be strong enough to support the wheel mounted on it and to withstand the maximum anticipated wind stresses. Manufacturer's specifications are detailed and precise. Should you choose an alternate tower, look carefully at the stress specifications, and be very sure not to cut corners. Cost savings vanish when the machine has to be retrieved off the ground after a storm.

When building your own tower, use only high-quality bolts and hardware. On a well-built tower every bolt should be in tension. Bolts from an old tower may be fatigued and worn from tower stress and shouldn't be re-used. Consult an engineer or local concrete contractor on footing specifications. On Cape Cod, we use 3,500 pound compression concrete for towers under 35 feet tall.

As to choice of building materials: wood looks nice, but is functional only in dry climates like the Southwest. In locations with any moisture at all, it's better to go with steel. We've tried a number of wooden towers (see the fifth *Journal*), but I don't believe any of the designs will last longer than eight years. Preserving wood is an expensive and potentially poisonous way to add a few years to your tower. On the other hand, in the Southwest, I've seen redwood and other wooden towers that are still sturdy after 70 years. But here we have decided to go with steel. It's dependable and virtually maintenance free, and most steel towers will outlive you. A final hint about towers: hoisting the underground pipe assembly for repair and maintenance is much easier if the tower height is a few feet greater than the longest section of drop pipe and pump rod.

The Well Seal and Pump Rod Assembly

The submerged positive displacement pump or piston pumps are generally the cheapest and most versatile water movers. Above-ground pumps that suck water up are easier to install, but even the most efficient suction pump can create a negative pressure of only one atmosphere. Theoretically this means that at sea level you can raise a column of water 32 feet by suction, but, as it turns out, friction losses and temperature changes render a suction pump incapable of pulling more than 22–25 feet.

The linkage between the mill and the pump cylinder is called the pump rod. The pump rod begins with a shaft that extends from the gearbox, through a swivel. This swivel allows the upper rod to turn with the yaw of the machine without rotating the entire pump-rod assembly. This shaft connects to the red rod. Generally a wooden (ash is most common) 1″ x 1″ piece, the red rod is designed to be the weakest link, or fuse, in the system. If anything goes wrong above or below it, the red rod will usually break, minimizing damage to other more expensive or less accessible parts of the mill. The red rod extends downward and connects to the polished rod which passes through the packer head or standpipe and the well seal. The well seal is just that, a simple expandable cap designed to keep dirt, insects, small animals, and other detritus from falling into and contaminating the well and water supply. The polished rod is usually made of brass to reduce friction. Brass serves to reduce corrosion as well, which is important in a part that works in both air and water.

At the bottom of the pump-rod assembly is the sucker rod, which connects to the pump plunger or leathers. Shallow wells (less than 100 feet) will generally use cheaper, solid steel rods. One-hundred to 250 foot wells will use hollow "Airtite" rods for buoyancy, and those deeper than 250 feet make use of light, buoyant oak or ash rods.

The Drop Pipe or Pump Cylinder

Usually the well driller cases the well. This is a must in sandy terrain like Cape Cod. The drop pipe, which can be a good grade galvanized pipe of any size, is then lowered to the desired depth. The drop pipe screws into the pump cylinder at the bottom. At the top it is screwed into a tee or coupling which keeps it from dropping into the well. The drop pipe should be slightly larger than the cylinder to permit removal and replacement of the pump leathers without having to pull up the whole pipe. It is important that the drop pipe be smooth on the inside, otherwise, replacement leathers will be damaged when the plunger is lowered back into the cylinder.

You can purchase either open- or closed-top cylinders. The closed-top cylinder is less expensive but since the plunger and leathers can't be pulled out to release the water in the drop pipe, you will be forced to pull the entire weight of the water column to replace the pump leathers. This comes to about five pounds per foot of two-inch pipe and can only be used in shallow wells.

The plunger diameter and length of the plunger stroke are major factors in the windmill's pumping capacity. Standard cylinders range from 1⅞ to 4 inch diameters. It is best to stick with a 1⅞ inch cylinder if possible, to permit leather removal through a standard 2 inch drop pipe. Pipe costs can scale rapidly above 2 inch diameters. In my area, 2 inch is $3.19/foot and 2½ inch is $4.80/foot, a 50.5% increase. The stroke of the windmill is the distance that the plunger moves up and down. A short stroke enables the windmill to begin pumping in light breezes, but in stronger winds a long stroke allows for greater volumes of water to be pumped. Many gearboxes are designed to permit stroke adjustment.

It is usually wise to put a screen just below the cylinder to prevent sediment from entering the cylinder and damaging the leathers.

The Packer Head or Standpipe

Once water is lifted, it is pushed through the drop pipe to the surface, and out through a tee or discharge pipe. Before discharge, water can either continue to be lifted into a standpipe (Figure 2), or can be diverted at a seal on top of the drop pipe known as a packer head. The standpipe is used when water is being delivered horizontally to storage. The height of the standpipe depends on the desired head or pressure needed to transport the water. When water is being delivered to an elevated storage tank, or when a seal is desired over the drop pipe to guard against contamination or vandalism, a packer head must be used. The packer head is an inexpensive fitting that seals the drop pipe and prevents overflow. Needless to say, in freezing conditions, the use of a standpipe would be foolish. The packer head would need to be protected in an insulated, underground housing.

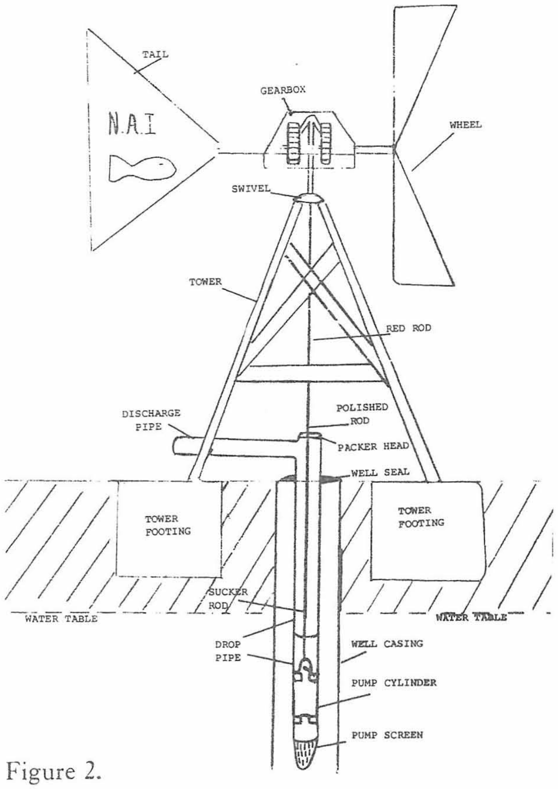


Figure 2.

A Water-Pumping Windmill with Standpipe.

TRANSPORT AND STORAGE OF WATER

Once water has been brought to the surface, what next? How do you get it to the desired end-use location, at the optimal pressure and necessary flow rate? This section will touch on the types of options in this phase.

Whether water has been lifted by suction, or by positive displacement, the best way to build up water pressure is to raise the water to a greater height than the place of end use. This can be done by pumping it to a tank either on a nearby hill or elevated on a tower. Every foot of elevation gives you about .43 pounds of pressure per square inch (psi). In other words, it takes 2.3 feet to get one psi. Most household applications require 18 psi, or about 41.5 feet of head.

The easiest way to pump water into a raised tank is to extend the drop pipe to a height greater than that of the top of the tank. The upper limit of a standpipe is the height of the pump-rod swivel, or the top of the tower. The disadvantages of this system are that it eliminates the fuse or red rod, and in addition it limits transport to pathways below the height of the standpipe.

If elevation is a problem and you don't want the hassle of constructing a tank, you can always use the simple and proven scheme of moving water to an on-the-ground holding tank that is coupled to a pressure tank through a small electrical centrifugal pump. In this way, the windmill still performs the major work of bringing water to ground level, and electricity is needed only for the relatively minor job of building up pressure. The larger the pressure tank, the less often the centrifugal pump will have to operate. The pressure tank should be close to the house to save on the amount of larger-diameter pipe required to handle the pressure tank outflow.

Pipe frictions must be considered when choosing the proper size plumbing for water transport. This is a matter of assuring that the psi is still adequate after friction losses in transport. Consult a standard schedule 40 steel-pipe friction chart or talk to your local plumbing supplier to avoid this simple but potentially costly error.

Elevating a storage tank is not as awesome a task as it might seem. A 5,000-gallon tank can be rolled up a moderately sloped hill by several people. You can pull a tank on to the tops of driven posts with block and tackle, and then build a platform underneath. Another simple scheme involves gradually building up the tank from underneath with alternating railroad ties.

The simple rule of thumb in tank selection seems to be in accounting for worst case demand. You can assume a daily rural per capita need of 50 gallons. In the Southwest, windmill people consider a ten-day stored supply safe. You'll wish you'd planned for excess storage capacity if a fire should break out. You should always plan for enough head to wet down your roof.

SELECTING THE MILL

Decisions about the proper mill are based on three basic considerations:

1. How deep is the water (of how much life is required)?
2. How much volume is needed?
3. How fast does the mill have to pump?

Wells and well technology are beyond the scope of this article. There are a number of do-it-yourself techniques for building wells. The VITA manuals are excellent guides for such schemes.[4] Depending on circumstances, you can drill, drive, or dig your own well. It is sometimes best to hire this job out. Professional well drillers can get the job done in a short time. The driller should tell you the drawdown or the rate at which the water is replenished at different depths. This is more critical in high-speed, high-volume electrical pumps, but it is useful information if you are coupling a submersible pump with your windmill.

Once you have your well, you need to determine the depth to water, and to add ten feet for pump submergence. Then calculate how high you need to lift the water to obtain the necessary end-use pressure. The distance from pump depth to the upper height is the total elevation (see Figure 3). Again, the required lift can be calculated by determining desired end-use pressure and multiplying by 2.3 to get the minimum necessary storage height. With the answer to this question you have your necessary head.

The required water volume can be computed by consulting plumbers, farmers, or neighbors. Plan for water use beyond per capita needs, as coverage against fires, etc. Finally, calculate the worst case rate demand, remembering that storage can help save on this item.

When you have these three figures, you are ready to pick the windmill best suited to your circumstances. I shall discuss four models currently available: the New Alchemy Sailwings, the Aermotor, the Baker, and the Dempster. Two other water pumpers are available commercially: they are the Bowjon, a low-volume air-lift pump, and the Sparco, a small (58 pounds) low-volume machine. As of this writing, I have had no personal experience with the latter two mills, and am unable to comment on their performance. Addresses are included at the end of this article, however.

New Alchemy has designed, developed and demonstrated two successful, low-cost, water-pumping windmills. Our sailwing windmills (see the fifth *Journal*) were developed to meet the need for a low-cost, reliable pump that could be constructed using local skills and readily available materials. One mill is currently operating a low-lift (5 foot), high-volume aquaculture pump on Cape Cod and the other, implemented jointly with the Arca Foundation and the Zen Center, is irrigating a farm valley in California with a high-lift (130 foot), double-acting piston pump. Both mills cost under $1,000 to construct with pumps. This figure could drop proportionally with resourcefulness.

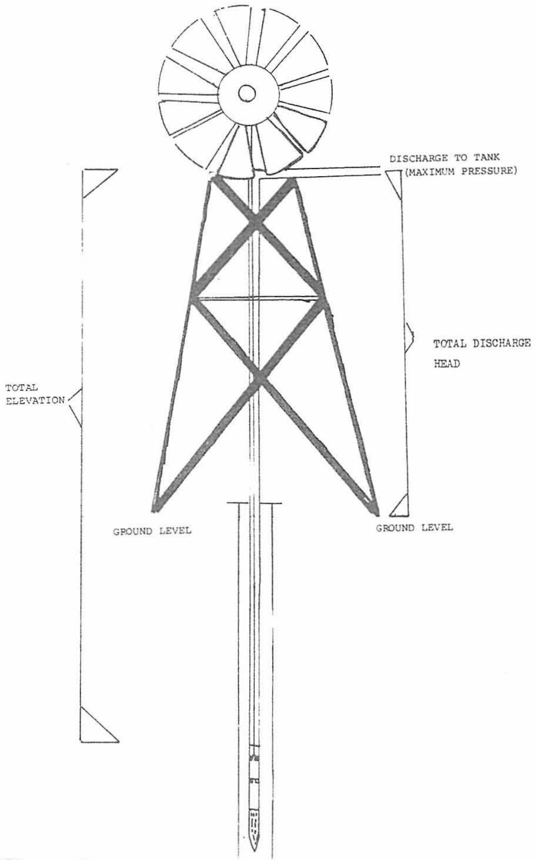


Figure 3.
Total Elevation and Total Discharge Head of a Water-Pumping Windmill.

The sailwings are proven, reliable machines. There are several vital considerations in choosing whether to employ this design, however. The mills are not available commercially, although the plans are yours for the asking, and the mill thus yours for the building. A second consideration is that, unlike commercial water pumpers, the sailwing does not have an automatic furling mechanism for high winds but must be hand-furled to prevent damage in winds over 40 mph, which means that it is less capable of operating independently. If you want to cut costs and build your own machine, are willing to tend it and to remain nearby, I recommend the sailwing highly. Aesthetically, it has everything else beaten cold.

On the other hand, the convenience of "off-the-shelf" windmills and replacement parts may be worth the extra costs. Baker, Dempster and Aermotor are the only active, commercial, metal multibladed water pump-

---

[4] See in particular: *The Village Technology Handbook*, 1970 by VITA, 3706 Rhode Island Avenue, Mt. Rainier, MD 20822.

ers on the market today. Each is proven and reliable with long anticipated lifespans.

Aermotor is by far the largest manufacturer and accounted for 80–90% of all windmill sales in the late 1920's. They have since moved their factory to Argentina, and it is no secret in the industry that the quality has been reduced in the move. They are currently known to be cracking down on deficiencies, and do offer materials and workmanship guarantees for one year. Baker mills, which are manufactured by Heller-Aller, are less costly than Aermotor and have excellent sales and service people and also offer a one-year guarantee. Dempster too makes an excellent machine, and offers a limited five-year parts and construction warranty.

Each of these companies provides elaborate and detailed literature on how to select the correct model and size for your needs. Figure 4 is a typical chart of pumping capacities in a 15 mph wind. It shows that by mixing and matching various windmill and cylinder sizes you can come up with a combination that best meets your needs. It is important to note that this and similar charts are based on the long stroke of the windmill. This is done in order that the respective manufacturers will look their best on paper. An adjustment to a shorter stroke will result in a reduced pumping capacity, but the mill will start up in lower winds. Since few of us ever see 15 mph *average* winds, it is better to choose from the chart on the basis of short-stroke measurements if they are available. Aermotor's pump chart, for instance, indicates that a change from the long to short stroke will increase your elevation by one third and will reduce your pumping capacity by one fourth.

The best rule is to pick the largest wheel and the smallest cylinder for your situation. This not only allows for start-up in low winds, but minimizes the mechanical strain on the system as well. Yet another critical consideration is that if winds are 12 mph on the average, the mill's capacity is reduced by 20%, and in 10 mph average winds, the capacity is reduced by approximately 38%. It is essential that you know your winds.

Figure 4. *A Typical Chart of Windmill Pumping Capacity*
Wind Rotor Diameter

Cyl.	*6 ft.*		*8 ft.*		*10 ft*		*12 ft.*		*14 ft.*	
Size	*Elev.*	*GPH**	*E*	*GPH*	*E*	*GPH*	*E*	*GPH*	*E*	*GPH*
1⅞	120	115	172	173	256	140	388	180	580	159
2	95	130	135	195	210	159	304	206	455	176
2¼	75	165	107	248	165	202	240	260	360	222
2½	62	206	89	304	137	248	200	322	300	276
2¾	54	248	77	370	119	300	173	390	260	334
3	45	294	65	440	102	357	147	463	220	396
3¼	39	346	55	565	86	418	125	544	187	465
3½	34	400	48	600	75	487	108	630	162	540
3¾	29	457	42	688	65	558	94	724	142	620
4	26	522	37	780	57	635	83	822	124	706

* Gallons Per Hour

Needless to say, tower height comes into play in this figure and you should select the tower accordingly. It is best to purchase the tower that is manufactured for your chosen windmill.

If, for example, you have a demand for 250 feet of head and 800–1,000 gallons of water per day, and if the wind averages 10 mph for five hours per day, you will have to choose a 12-foot mill with a 1⅞ inch cylinder. If the same site were subject to 12 mph winds for five hours per day, a 10-foot mill on a lighter-weight, less-expensive tower would be sufficient. This means a cost of about $1,000 less for the wind speed increase of 2 mph. Of course costs could also be cut $1,000 by halving water consumption, but the point is, to know your winds, and to think hard about your water use.

Joe Carter, of *Wind Power Digest,* calculated that according to local pump dealers, a typical submersible pump for this application would cost about $900 in 1979. Operating costs would amount to about 2 kw for one hour per day at $.05 kwh, or $36.50 per year. If you add in the lifespan of the pump which, on the average, is six years, with a replacement cost of 40–50% vs. a 20-year conservatively estimated windmill lifespan, after 20 years you will have replaced three submersibles, costing about $1,215. Taken together over 20 years with a 7% electricity price inflation you have $132 per year in the twentieth year for the submersible compared to $20 to $80 per year for the windmill, depending on maintenance costs. This crude analysis supports Unger's findings.

One final note on selecting the mill: Don't discount a windmill just because your well is not at a great wind site, or for that matter in a place (like under your cellar) where it would be hard to locate a tower. Windmills can be fairly versatile and in some cases can be offset many feet from the actual water source (Figure 5). There are simple techniques for combining a submersible electric pump with a windmill. You can use a gasoline or electric-powered pump jack for emergency back-up pumping power. A large mill and a small mill, or booster mill, can be employed in tandem to give added capacity for transporting water over large distances. Windmills have broader application than most people realize.

ERECTING YOUR WINDMILL

The best first step is to sit down and try to think through the entire process of erecting the mill. Good planning can save time, money and extra trips to town. The well should be built first, and the water tested right away. Then you can assemble the basic tools needed for the job. These include lots of heavy rope, some pulleys and chain, hammers, wrenches, vice grips, drift punches, screwdrivers, shovels (maybe a crowbar), pipe wrenches and pipe dope (affection-

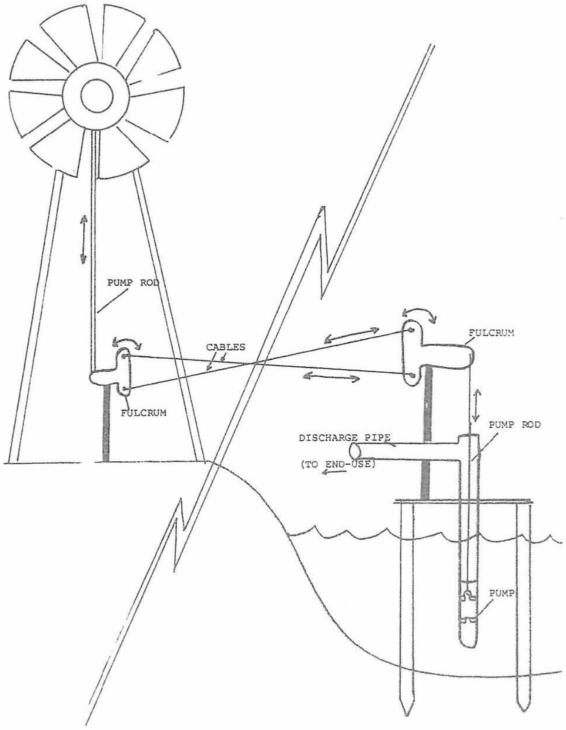


Figure 5.
A Water-Pumping Windmill with an Offset Pump.

ately known as turkey shit at our plumbing supply shop), and a good tape measure. A transit will help for leveling the tower although a long level can do the trick.

Once the well has been cased, the fun of putting in the cylinder and drop pipe begins. Invite a few friends. This is definitely not a one-person job.

You can either build your tower now or else build a temporary platform for raising your drop pipe sections vertically before they go down the well. We'll get back to tower construction shortly.

For the moment, first connect the cylinder and screen (*never, never, never* put a wrench directly on the cylinder—grab the coupling) and screw in the bottom section of drop pipe. Apply pipe dope liberally to the threads; it pays over the long run.

Lowering the drop pipe is both exhilarating and nerve-racking. It takes a lot of patience. If you are unfortunate enough to drop a section down the well, you are sidetracked into an auxiliary excursion into fishing for it which, at this juncture, is no fun at all. Tie your tools to your belt, and keep all possible contaminants away from your well casing. One easy way to lower pipe is with an angled bite with a pair of pipe wrenches. You can also use a pipe holder, or a pipe clevis. These hints take on added significance with each added pound of pipe that you lower into the well. Attach each pipe section with great care so you don't have to pull it all back up again. Once you've reached the desired depth, fasten on a tee and rest the whole assembly on the lip of the casing. A typical installation will have at least one pipe section below the water table as insurance against drawdown. If you are coupling a submersible into the system, then be sure to have the well people calculate drawdown for different depths.

At this point, you can choose either a standpipe or a packer head. Right now I'll assume you are choosing the more common, latter strategy. The next step is seating your bottom check valve and connecting up your pump rod.

Seating your bottom check is as simple as dropping it down the drop pipe (literally) as long as you do it right side up. Make sure the threaded side is up and the valve is clear of cotton or paper ball protectors. The threads are useful when leather replacement becomes necessary, as we'll discuss in the last section. Drop the plunger down the pipe, and listen for the thud. Now attach the upper check to the successive pump rod sections and lower away continuing to add until you are near the top of the well. Slide the packer head over the rod and tighten it on to the drop pipe.

Now you are ready to erect the tower.

Directions for raising the tower are well explained in the manufacturer's specifications. The key is to be certain that the surface over the well casing is level. The slightest angle will damage the pump rod, and definitely affect the mill's performance.

Most tower footings are about four feet deep. One construction method is to build the tower piece by piece, to level and plumb, and then to pour the concrete. Another is to build the tower on its side and gin pole it erect and into place. I recommend the first method as it is easier to square up the tower. Lifting the rig is generally a more hazardous and expensive operation, requiring a truck, tractor, or crane.

The goal, in either case, is to get the tower vertical and into its holes. Shim it to level and pour the concrete. Give the footings a day to set and you are ready to lift the machine. Again, you can use a crane, or heavy machine if one is available, but it isn't necessary for the average water pumper.

If you are a bit more adventurous (or poor), get a sturdy piece of three-inch pipe and chain it firmly so that you have about six or eight feet above the tower top. Block it at an angle so that the pipe end is directly over the tower center, but the pipe will not obstruct the machine as it is lowered into the top fittings. Attach the block and tackle or pulley and thread through the lift rope before you stand the pipe up, or you are liable to be shinnying up some time later. The manufacturer's directions should take over from here. Grease the gears, and pull the machine up. A guide rope is useful to help keep the machine away from the tower during the ascent. One person topside should be able to guide the

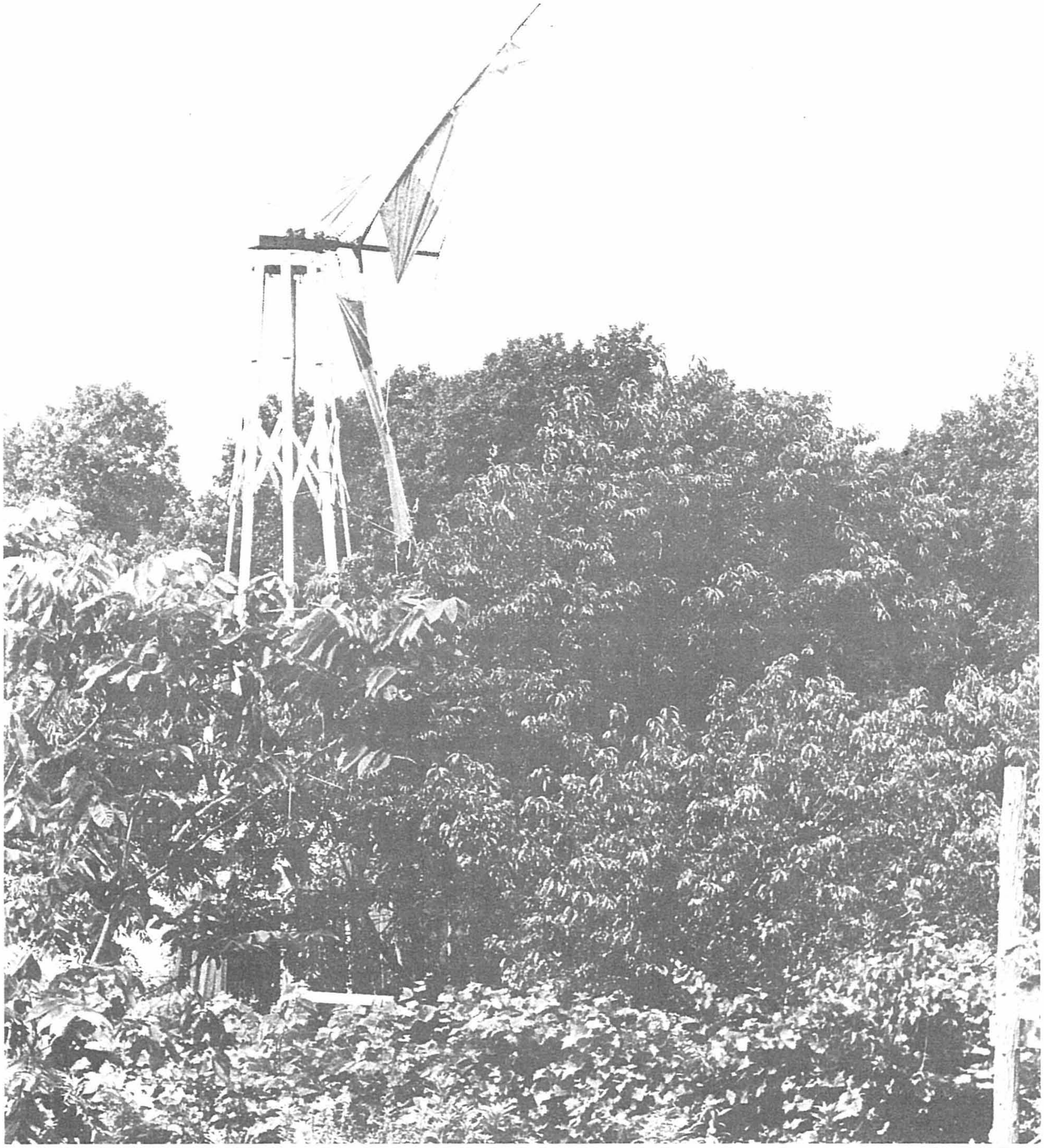


Photo by Hilde Maingay

machine into its supports. Now you can fill the crankcase with oil and attach the brake, tail, and furling mechanism. Assemble the wheel with care and attention to the order of each part. The sail parts should be weighed if they are not marked accordingly, to assure a balanced rotor. Line up the parts carefully to avoid wobble later on. Tighten it down slowly, rotating the wheel around a few times until it's been tightened evenly and firmly.

To connect the machine to the pump rod, turn the wheel to the *bottom* of the pump stroke, furl it out of the wind, and attach the pump rod and swivel. While sizing up the red rod for proper length, make sure that the pump rod is blocked at least two inches higher, so that the top cylinder leathers will not touch the bottom plunger. Cut the sucker rod and through bolt it in. It is best to give the wheel a few manual turns to guarantee a smooth and unobstructed stroke. With a little luck, water should be soon forthcoming. Hook up the lines and you are set to go.

MAINTENANCE

As for an annual maintenance check, a few tricks will suffice. Always use *SAE 7 weight non-detergent oil* for gear lubrication. A thicker oil will gum up and spill out, and will also allow metal fragments to float about in suspension, rather than sinking harmlessly to the bottom of the case. When changing the oil during the annual tune-up, a magnetic drain plug can be useful for picking up fragments. Clean the pan with kerosene, drain and refill with fresh oil. Check bearings and gears, and if one of a pair is broken, replace both. This insures against uneven stress and wear over the machine's lifetime. The annual tune-up should include a complete tower retightening.

When and if you ever need to replace the leathers, simply let the upper check down into the lower check threads, twist, and pull out. Be careful not to bend the pump rod and remember, disassemble as each coupling emerges from the well. Always coat new leathers with vaseline or a similar nontoxic lubricant. Give the new leathers a chance to soak and swell, and again, give the mill a few turns before unfurling, as a quality control check.

Once operational, it is still a good idea to familiarize yourself thoroughly with the manufacturer's charts and parts lists, or in the case of the sailwing, to reread old *Journal* articles. Two excellent sources of information can be found in a series on water pumping by Joe Carter of the *Wind Power Digest* staff (issues 14, 15, 16—1979), and in an excellent booklet put out by the New Mexico Energy Institute in Las Cruces. The author of this booklet, called *Selecting Water Pumping Windmills*, is a gruff but charming fellow named M. I. "Ras" Rasmussen. Ras teaches a top notch, two-weeks, hands-on course on water pumping windmills twice each year at New Mexico State University, which is a must for anyone who's contemplating a future in this business. It is a first-class learning experience taught by a true master, and is the only course of its kind any where in the world.

A few other useful addresses are included to help you on the road to water self-sufficiency.

Good Luck!

USEFUL ADDRESSES

Aermotor
Division of Valley Industries
P.O. Box 1364
Conway, Arkansas 72032

Baker
The Heller-Aller Company
Perry and Oakwood Streets
Napoleon, Ohio 43545

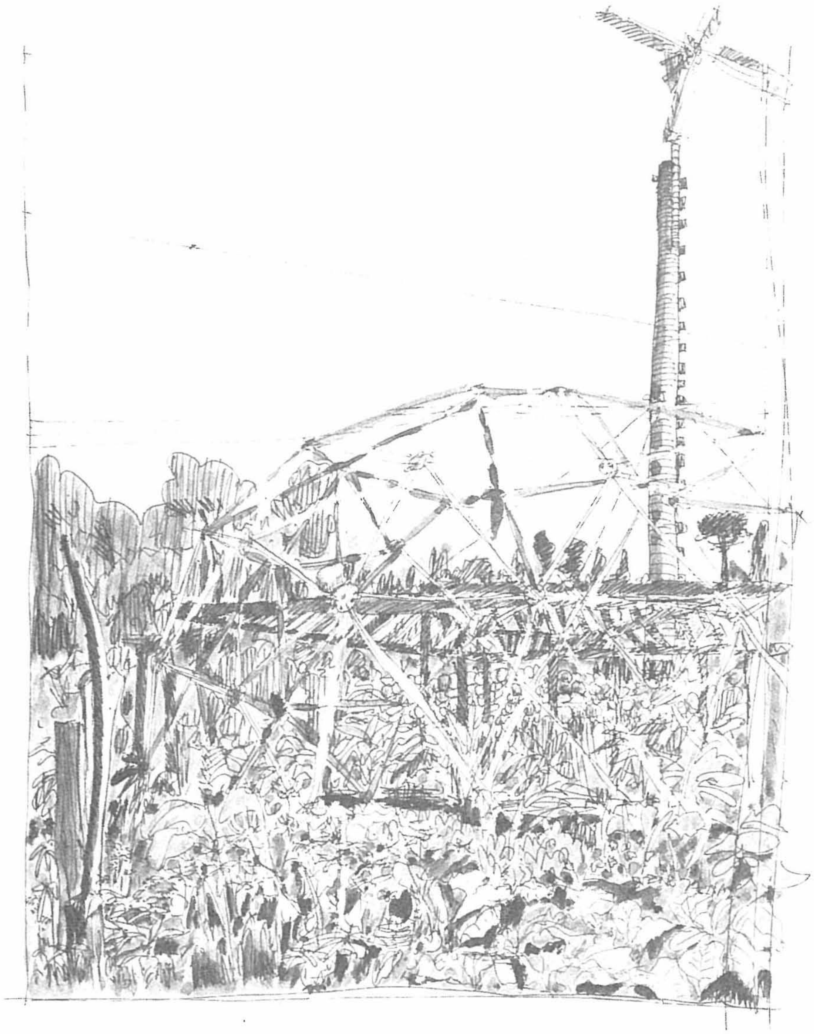
Bowjon
The Bowjon Company
2829 Burton Avenue
Burbank, California 91504

Dempster
Dempster Industries Inc.
P.O. Box 848
Beatrice, Nebraska 68310

SPARCO
Distributed by Enertech
P.O. Box 420
Norwich, Vermont 05055

Wind Access Catalogue
Wind Power Digest
54468 CR 31
Bristol, Indiana 46507

Windmill Course
New Mexico State University
Agricultural and Extension Education
P.O. Box 3501
Las Cruces, New Mexico 88003



Drawing by Jorge Bueno

An Integrated Wind-Powered System to Pump, Store, and Deliver Heat and Cold

Joseph Seale

Energy comes in many forms. Atmospheric wind energy is kinetic energy, the energy of mass in motion. The best-known way to harvest this energy and channel it to human use is with sails or airfoils such as we see on sailing ships, glider planes, and windmill rotors. Sails and airfoils transform the kinetic energy of the wind into mechanical energy, or work, which is force exerted through a distance, or equivalently twisting force (torque) exerted through an angular distance. For example, mechanical work pumps water by exerting force on a piston through the distance of many strokes, or mechanical work grinds grain by exerting torque on a millstone through the angular distance of many revolutions. These two examples are traditional windmill tasks.

In 1978, starting from first principles of physics and economics, I set out to identify and describe a practical, wind-powered system that might fulfill a widespread human need and to determine to which uses windmill energy is best adapted. The solution stems in part from the starting form of energy, which is mechanical, and depends on where wind energy is obtained which is usually on the top of a tower, and also on the distance of the windmill tower from a location of end use. The solution further depends on the variable availability of wind energy over time and consequently on whether a task can be performed at irregular intervals, as, for example, pumping and milling, so that the result of the task such as pumped water or flour can be stored, or whether the energy of the mill instead must be stored in order to perform the task on demand.

This paper documents the outcome of my search: a heat/refrigeration pump and thermal storage system. The one that follows documents a dead-end attempt at an air compression heat/refrigeration pump and mechanical energy storage/recovery system that eventually evolved into the current concept. Started afresh, this same kind of search could probably lead to entirely different viable systems and many other dead ends as well. Much of the message of this paper concerns not the particular system but the process of breaking with traditional assumptions, as will be necessary time and again in many contexts in order to build a sustainable economy based on renewable resources.

If the concepts described in this paper continue to prove successful (a big "if," knowing how easily small matters can trip up the best thought-out plans at any stage of development), we hope they will lead to several years of applied research, design, and development, culminating finally in designs mature enough for manufacture and widespread practical use. The reader is warned against believing that the seemingly simplest concepts are simple in execution. There are many ways to build systems that work poorly, briefly, or not at all, and comparatively few ways to build systems that pay for the trouble, materials, and energy of construction. Fortunately, those "comparatively few" ways are still an infinite number.

THE PATH SUGGESTED BY THERMODYNAMICS

Energy production and energy use have become increasingly specialized and separate. And yet from the perspective of whole systems, effectively integrated energy systems require attention to the detailed nature of both energy resources and end uses. The recent abundance of energy has created no historical demand for such attention. Our maladaptive habits linger on so that concern for energy in our society is still overly abstract and quantitative at a time when effective energy strategy demands attention to particular and qualitatively different tasks. In the case of wind energy, the current near-exclusive focus on electricity generation cannot be taken as evidence of the superiority of electricity for all wind-energy uses.

Electricity is an energy form that is easy to control, transmit, and convert to many other forms. Thermodynamically, electricity is a zero-entropy energy form, which, by definition, means that its unavailability to do work is zero. In principle, electricity can be entirely converted to mechanical work. As the thermodynamic definition suggests, mechanical energy, or work, is the fundamental standard against which physicists measure the quality of all other forms of energy.

Since the energy delivered directly by a windmill rotor is mechanical work, one question arises. Might that form of energy be used directly to perform some task of major economic significance rather than being converted to electricity? The answer is emphatically yes. In the United States, fully 35% of delivered energy (strictly, enthalpy, which is gross energy without regard to quality of the end-use form) takes the form of heat to warm things and cold to cool things to temperature differences from the surrounding environment of less than 100°C. (180°F. differential).[1] The most energetically efficient known method to move heat across such small temperature differentials is by mechanical heat pumps.[2] Because of its high thermodynamic quality, one unit of mechanical energy driving a heat pump can move several units of low-quality thermal energy, the actual quantity increasing as temperature differential goes down. Depending on conditions, one unit of mechanical energy can move two to four units of thermal energy, resulting in an equivalent refrigeration of two to four thermal units, or a refrigeration coefficient of performance (C.O.P.) of two to four. The resulting heating on the other side of the heat pump is one unit greater, three to five thermal energy units, since the energy that drives the heat pump appears as extra heat output. (Note that usage of the term "heat pump" here includes both refrigeration and heating applications. Some authors apply the term only to heating end-uses while calling the same device a refrigeration unit when cooling is the end-use.)

THREE PRACTICAL HURDLES

While windmill rotor power is ideally suited to heat pumping on theoretical grounds, there remain three major practical questions to be answered.

Transmission

The first question concerns transmission. Can heating and refrigeration be delivered to where they are needed in a direct and efficient manner? For short to medium range applications (up to a few hundred meters or a kilometer, depending mostly on scale), the answer is yes. Any vapor-cycle refrigerant can serve as a medium to carry heat from the place where it evaporates and to deposit heat where it recondenses. Heat pipes utilize

---

[1] Amory Lovins, *Soft Energy Paths: Toward A Durable Peace* (1977, Friends of the Earth, Inc. and Ballinger Publishing Co.) pp. 80, 81. Figures for other countries run even higher. 37% for France, 39% for Canada; 50% for West Germany; 55% for United Kingdom.

[2] See *Heat Pump Technology*, June 1978, prepared for the U.S. Dept. of Energy, pp. ii-v. The result is given for electrical heat pumps, whose efficiencies are lower than for mechanical heat pumps because of minimum 10% (3-phase) or 15% (single-phase electrical-to-mechanical conversion losses (ibid., p. 48). The study shows that in terms of primary energy, i.e. fuel burned at the electrical power plant, electric heat pumps are not big fuel savers or money savers. Electricity generation, distribution, and conversion losses totaling 70% eliminate the major advantages of the final mechanical heat-pumping step. Fortunately, none of these losses apply to direct windmill-driven heat pumps.

evaporation, vapor transport, condensation, and capillary or gravitational liquid return to transport heat efficiently in this way. A vapor-cycle heat pump is essentially a heat pipe in which vapor flow is boosted mechanically to cause heat to flow "uphill" against a temperature differential. Insulated pipelines carrying refrigerant gases are a practical means of hot and cold delivery over moderate distances. The mechanical work that moves the gases can take place in a tower-top compressor linked directly or through gears to a windmill rotor shaft, and pipelines deliver the end products (hot and cold) to chosen destinations.[3]

Storage

The second question is, can heat and cold be stored at a practical cost for use in periods of insufficient wind? For many thermal end-use applications, thermal storage is much cheaper and simpler than any indirect energy storage, such as electricity-related storage. This applies particularly to the storage of cold, which is accomplished through the fusion of ice or inexpensive solutions with lower freezing points, as required.[4] Practical storage-time increases with scale since large objects have lower surface-area to volume ratios, hence inherently longer thermal retention, than smaller objects. With a reasonable thickness of good insulating foam, seasonal thermal storage becomes practical on a moderate scale. For applications where uninterrupted operation must be insured, significant investment in long-term storage is justified. The alternatives are either to invest in a much larger windmill rotor (easily five to ten times the swept area may be required for a system with two weeks' storage as opposed to ten weeks' storage) to utilize light summer winds to meet maximum thermal load demands, or to invest in a motor-driven back-up compressor. In contrast to refrigeration, space heating demands tend to be much better correlated with strong winds, so heat storage can be smaller. In addition, back-up heating systems are much cheaper than back-up refrigeration components.

Rotor/Load Matching

The third question is more subtle. Can a windmill rotor operate efficiently driving a heat pump, since the available torque from the rotor and the optimum rotation speed vary constantly with windspeed? Unmodified, a compressor will exert a torque that is almost independent of rotation speed. The optimum back-torque for a windmill rotor should remain quite low up to moderate rotation speeds and then increase steeply with further speed increases. Statistical modeling of performance of rotor/compressor combinations has shown that for economical rotor types the rotor efficiency loss is greater than 40%, even assuming the simple "fix" of an automatic clutch to permit rotor start-up without load.[5]

The most effective solution to this problem is a special modification to the operation of a refrigerant compressor to provide a low starting load and steeply increasing high-speed torque. Electronically switched electromagnets control the closure of the intake valves of the compressor cylinders, causing the pistons to compress on some but not necessarily all strokes. At low speeds, no compression takes place, so shaft torque is low. As speed increases, compression begins to take place infrequently, then more and more frequently until, at maximum speed and torque, every stroke is a compression stroke. A flywheel smooths the jitter in torque when the pistons are alternating between compression and no-compression strokes. The electronic circuit is simple and operates entirely from the power of timing pulses from a magneto turning with the compressor shaft.

ECONOMIC PROSPECTS

No wind-power system has combined the three features of refrigerant gas thermal transmission, thermal storage, and compressor matching to windmill rotor characteristics, into a working, self-contained energy system. To our knowledge, no wind-power system has used even one of these features. We believe that the total system described will be cheaper than any similarly advanced, total wind-electrical energy delivery system with comparable energy capability plus storage and/or back-up. Because of the additional advantages of high mechanical-to-thermal energy gain and end-usability of the system output, the proposed system should be directly competitive with existing utility-based thermal systems.[6] And for its price, the

---

[3] In case of a compressor on a horizontal axis windmill tower-head assembly that orients with changing wind direction, a two-way rotary pneumatic union is needed to connect gas flow to stationary down-pipes while allowing the compressor to turn with the mill. Such devices are manufactured commercially.

[4] Short-term cold thermal storage at freezing and subfreezing temperatures is commonplace in the food shipping industry. For an example of seasonal thermal energy storage we need only recall the unrefrigerated ice houses that once "powered" ice boxes in the northern United States throughout the summer.

[5] Computations by the author. Rockwell International, the contract monitor for the Small Wind Energy Conversion Systems (SWECS) program at the Rocky Flats plants, sponsored by the U.S. Department of Energy, is conducting a computer based study of statistical performance in variable wind regimes of nonoptimum compromise matches of rotors and loads. The author originally undertook this study to evaluate alternative approaches to wind-powered heat pumps.

[6] See footnote 2, particularly the 70% net losses from gross primary energy to electricity delivered to the heat pump. Lovins (op.cit., p.88) shows that capital "losses" to electricity transmission, distribution, and T & D system maintenance are about as severe as the total energy conversion loses of electricity production and delivery. Only about 29% of residential electric bills in the U.S. and 55% of commercial electric bills, pays for electricity. The remainder pays for delivery to the customer. We find in this a strong argument for the long-range diseconomy of wind-powered systems that rely on utility system energy back-up. The marginal costs to a utility in equipment and extra capacity are high since the demand of such users comes all at once, at the end of a long calm spell. See J. Seale, "Sun,Wind and the Power Company," *CoEvolutionQuarterly*, Winter 1978/79, pp. 30-31.

proposed system, in varying embodiments, will perform such diverse tasks as space heating; accelerated drying of lumber, tobacco, raisins, etc.; air conditioning; food refrigeration and freezing; and ice manufacture.

A FIRST EXPERIMENTAL EMBODIMENT

Limited technological, financial, and the human resources available at New Alchemy argue for a modest beginning. We intend to concentrate initially on exploring the novel aspects of the proposed system in an easy-to-manage, small-scale demonstration using one of our windmills and an air compressor modified to match the characteristics of the windmill. The compressor will be placed near the rotor and coupled via insulated pipes to freezer and to aquaculture tanks that are to be heated. Both are at ground level. Insulation will be placed in hermetic sections of coaxial pipe and the insulating space will be filled with a heavy gas that affords better insulation than air. The freezer itself will hold approximately two cubic meters (70 cubic ft.), about one-third of which will be filled with containers of salt brine for subfreezing thermal storage. Insulation thickness will be abut 30 cm. (one ft.).

The food-freezing component will be useful for seasonal crops and for the fish grown by New Alchemists, complementing on-going work and providing a demonstration of some of the major potential applications of the system. Winter heating of aquaculture breeding tanks by the heat pump will encourage survival and reproduction for fish sensitive to cold temperatures. Heat that leaks from the breeding tanks will help buffer the climate in the Ark and should enhance productivity in cold periods.

MARKET AND COMMERCIALIZATION RESEARCH

In the early stages we intend to direct a modest amount of effort to exploring markets for embodiments of the thermal system concept with commercial potential. We plan to spend comparatively little money at this stage relative to what could be spent on a "rigorous" analysis. Rigor is illusory when it comes to projecting what investors will pay for technologies that are not at the mercy of OPEC politics. More philosophically, what an "analysis" says that people will pay for renewable alternatives should not be the sole determinant as to whether those alternatives become available. Those who believe that human choice should guide economics need to take on faith that people will invest in well-designed equipment that accomplishes needed functions at an affordable cost in such a way as benefits the future as well as the next five years.[7] Such faith is scientifically unverifiable, being part of a larger irreducible synthesizing force called human will.

The task of market and commercialization research therefore will be to identify directions that are practical, useful, and affordable, and to facilitate choices among the most promising directions. The kind of research apparent in the descriptions in the next section should illustrate the kind of analysis to be extended in the future.

TENTATIVE FUTURE SYSTEM CONFIGURATIONS

There are two opposing constraints on the choice of the embodiment of a system for initial development. The commercial immaturity of large windmill rotors implies excessive lead times to develop a large-scale system. Conservatism on initial investments in a new area also favors smaller systems. On the other hand, both commercial and engineering constraints, like the short thermal-storage times practical in small systems, as mentioned above, dictate that the system not be too small. Listed here are the embodiments of four systems in order of increasing minimum scale. For the first and second, storage time is the scale-constraining factor. For the third and fourth, commercialization constraints dominate.

1. *Dairy milk refrigeration combined with cattle wash-water heating.* Ice thermal storage, bio-gas back-up. Sale of surplus gas. Option to use heat pump to achieve pasteurization temperature before chill.

In New England an average dairy herd has approximately 60 cows, each producing an average of 15 kg. of milk per day.[8] Specifications for a system capable of handling such a herd in 4 meters/second (9 miles per hour) annual average winds, and a reduced herd of 50 cows in 3.6 m./s. (8 mph) winds, demand a 10 m. (35 ft.) diameter rotor with a mechanical power capacity of 1,500 watts to the heat pump. For milk cooling combined with wash water heat to 35°C. (95°F.), a cooling coefficient of performance (C.O.P.) of three is currently achieved, along with a simultaneous heating C.O.P. of four.[9] These figures are used for the above specifications. Thermal storage consists of 55 metric tons of icewater contained in a 4 m. x 4 m. x 4m. (13 ft.

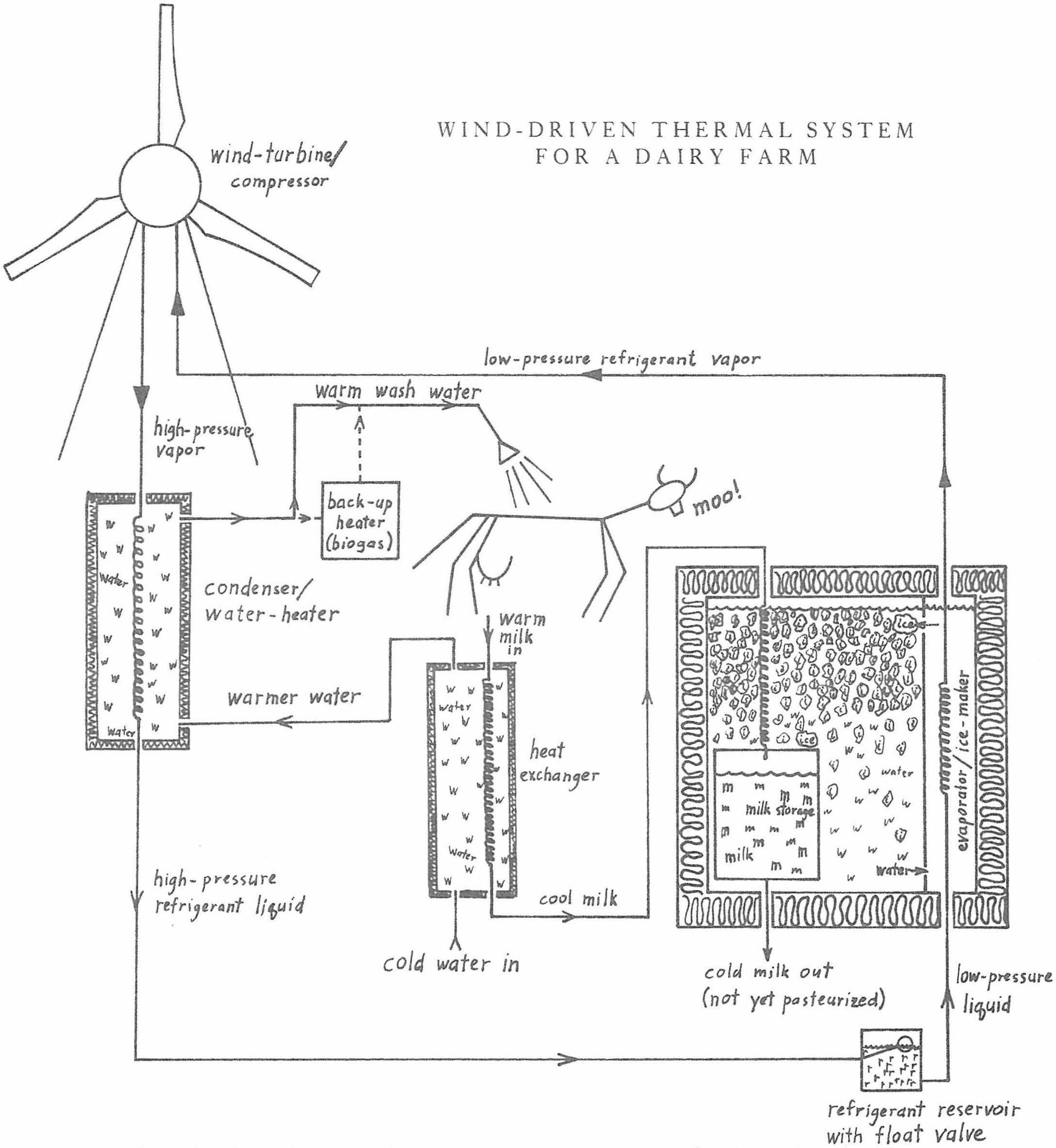
---

[7] We do not abandon our earlier contention that the best embodiments of the proposed system will be economically superior to competing technologies in the near-term, if whole-system economics is the criterion. But whole-system economics is unfortunately not always market economics. Thus, we appeal to a higher wisdom that must recognize unwise subsidies and simple avarice, and work in the context of these realities to achieve sensible and humane economic goals.

[8] Dr. Stanley Gaunt, U.S. Agricultural Extension Service, Amherst, Mass.; personal communication.

[9] Dr. Louis A. Liljedahl, U.S. Dept. of Agriculture, wind energy specialist; personal communication. Dr. Stanley Gaunt (footnote 8) also reports the rapidly growing use of heat pumps for this application.

WIND-DRIVEN THERMAL SYSTEM
FOR A DAIRY FARM



Principle: transfer heat from cattle wash water in two steps, first passive exchange, then by wind-powered refrigerant pumping. Use long-term ice cold storage, bio-gas heat back-up.

Notes: refrigerant lines are insulated. It would save energy to use wind-powered heat pump to pasteurize milk before chilling. The system shown is consistent with common farm practice to leave pasteurizing to a central milk distributor.

on a side) water tank (inside dimensions) with internal heat exchanger and milk tank. Insulation is 30 cm. (one ft.) thick urethane or other foam. Effective storage time at full use load is 90 days, sufficient for eight-to-one variation between the best and worst month average seasonal wind power fluctuation.[10]

With a counter-flow heat exchanger and warm-water storage tank it should be possible to exchange heat passively from incoming warm milk to incoming cold water, further reducing the work of the heat pump necessary to achieve final temperatures, especially in winter when the incoming water is cold. This combined with thermal storage could help improve year-round efficiency by a substantial factor so that the same windmill could service much larger herds, or so that a much smaller windmill would do the same job.

2. *Rural community locker plants for freezer space rental in possible conjunction with commercial food processing and storage.* Thermal storage at –21°C. (–6°F.) by freezing a eutectic salt (NaCl) brine. Heat may be used for nearby space heating.

The windmill specifications are identical to case 1. Refrigeration C.O.P. estimate: two. Thermal storage is also analogous: 55 metric tons of salt brine for 90 days at full use load with a high outdoor average temperature of 30°C. (86°F.). Freezer interior dimensions are 4 m. (high) x 5 m. x 7 m., with bottom 1.5m. filled by a salt brine pool penetrated by refrigerator pipes and passive heat pipes. Insulation is 40 cm. (16 in.) thick foam. User air lock. Design use load: 70 visits/day, two-minute stay, bringing in 2 kg. of food every other trip (proportioned two parts meat to one part fish to two parts watery vegetables, all presumed to enter at outdoor temperature, e.g., fresh harvest or slaughter).

For case 1, conduction loss through 30 cm. foam is less than 10% of the total thermal load, which implies that the diary system could be scaled down easily.For case 2, conduction loss through 40 cm. foam is 60% of the total thermal load, so that scale reduction would demand more insulation to compensate for poorer (larger) surface/volume ratio.

3. *Ice making plants for the fishing industry.* It will be practical to design for higher windspeeds at seacoast sites, as contrasted with cases 1 and 2. Ice is preferable to refrigeration for fresh-fish preservation since layering of fish and ice permits very rapid equilibration of fish to near-freezing temperatures without danger of freezing. Although heat can be sold for space heating while allowing a refrigeration C.O.P. of three, heat could be rejected to ocean water at a much lower temperature, permitting a refrigeration C.O.P. of at least five.

To justify the investment in harbor space, dock, loading equipment, etc., to service large fishing boats, a minimum commercial-scale ice plant might need to produce 2,000 tons/year.[11] Although this implies almost ten times the annual output of systems 1 and 2, several factors combine to keep the necessary rotor size down. With the availability of good seacoast wind sites, a reasonable design minimum average windspeed is 5 m./s. (11 mph) instead of 3.6 m./s. (8 mph). With condenser rejection to ocean water, a refrigeration C.O.P. of five is assumed. And the safety margins necessary, say, for a food locker with valuable contents and high cost of a thaw, will not be necessary for an ice plant that might have to lose a small fraction of its regular customers to a non-wind-powered competitor in a year with below average winds.

With these considerations, rotor size comes to 15 m. (49 ft.) diameter with a rated mechanical power of 10,000 watts. Storage capacity will depend on seasonal demand fluctuations as well as seasonal wind variability.

4. *Kiln drying of lumber or tobacco.* (Similar systems would be applicable to food drying, but as of this writing the author lacks concrete experience of food drying requirements on which to base even a tentative system description.) Vapor condensation and thermal recycling for top efficiency. No thermal storage or back-up.

In this system, hot and cold side heat exchangers operate in tandem as an air dehumidifier: the cold coils condense water, then the hot coils boost the dried air to a higher temperature than that of the moist air originally entering. Drying takes place in an insulated enclosure and the cycle remains closed except for the input of wet materials and the removal of dry materials plus water.

We lack data with which to estimate scale or performance of a system like this. The author has witnessed huge expenditures on fuel oil to dry tobacco in Maritime Canada. The winds there are the best in North America, and are very good by the tobacco harvest time in the fall. The demands for home space heating escalate at about the time that tobacco drying is completed. A hybrid drying/home-heating system would probably be necessary for good utilization and payback. Summer, the period of no demand, is the period of least wind.

---

[10] See P. C. Putnam, *Power from the Wind* (Van Nostrand Reinhold Co., 1948), pp. 90-91, for an example of seasonal variability in New England. The assumption of eight-to-one variation is conservative (i.e., safe). The calculations make a safety allowance for a year with 25% less than average wind power for the site, also indicated by Putnum's data (same pages). Data is available to research these assumptions much more rigorously.

[11] James W. Mavor, Jr.,Woods Hole Oceanographic Instituion: personal communication.

GLOBAL PROSPECTS

The technology growing out of such a program should be relatively simple and economical, encouraging small businesses to produce diverse subsystems (windmills, thermal stores, drying ovens, cold-storage warehouses, solar-plus-wind heated greenhouses) in a competitive market. While the United States is probably best equipped to support the costs of the early portion of the system learning curve, the knowledge produced will require technology of a scale and simplicity that is accessible to nations with less capital and fewer specialized engineers and technicians available. Wind-driven heat pumps and thermal storage systems should come to represent a significant quantitative step to a world-wide renewably based technology.

Whatever Happened to Compressed Air?

Joseph Seale

Everybody said that compressed-air energy storage for wind power was a natural and that somebody ought to try it. So we did. The first setback was suggested by theory, but we thought that we could turn that into an asset. Then economics, engineering details, and the available, state-of-the-art equipment were lying in wait and ambushed us.

Theory first. When you compress a gas, the work performed to squeeze it adds energy, causing temperature to rise. The temperature increase causes a proportional rise in pressure, with a resultant increase in the work required to compress the gas. If the compressed gas cools off before being used to run an air motor for energy recovery, then the pressure will be lowered and the extra work required for compression will not be recoverable. For compression to 7 atmospheres (100 pounds per square inch) the ideal theoretical efficiency limit for one stage compression and decompression is only 57%. The remaining 43% of the energy goes to pump heat.

Fine. Why not combine heat pumping with a mechanical energy storage and recovery system? Use the heat from the compressor to warm aquaculture tanks, the cold air exhaust from the air motor to freeze food, and the stored mechanical energy to run the blower motor for the rock heat storage system in the Ark. It looked like a superb example of synergistic, multifunctional use of equipment. We were very excited.

Enter the real world, real air, and real machines. Air contains moisture. As air cools upon expansion through an efficient air motor, ice sublimes out and freezes up the motor. There is a way around the problem with an air drying device—but that is expensive. Judging from the performance figures on motors, air motor manufacturers have found a cheaper solution; which is to make the motor so inefficient that most of the energy in the compressed air generates heat to prevent freezing. The most efficient combination of compressor and air motor that we could find is 8% efficient mechanically, and that is with an efficient two-stage compressor that cools the partially compressed air to minimize overheating and consequent excess compression work. Since most of the energy that might have been recovered mechanically goes to overcome motor freezing, the system makes a very poor refrigerator. Mostly, the compressor motor systems that we could buy degrade high-quality mechanical energy to low-grade heat which is of some utility, but not worth the price.

We considered the costs of compressed-air energy storage costs. A little math and physics shows that for a given strength of material (e.g., steel) used to make a compressed air tank, the quantity of material required varies in proportion to the volume-times-pressure capacity of the reservoir. In other words, there is no scale advantage or disadvantage for cost of materials, which is the major cost of large tanks. The following table confirms theory in practical terms:

1977 Prices,
Tanks Safe to 125 PSI

Volume, gal	*Cost, $*	*Weight, lbs*	*Cost/Volume, $/gal*
125	$ 338	296	$2.70
235	$ 504	500	$2.14
660	$1,523	1,225	$2.31
1,550	$3,146	3,200	$2.03
2,200	$3,893	2,200	$1.77

Our guess is that the largest tank uses a reduced quantity of higher strength, more expensive steel to achieve lighter weight at a slightly better cost.

Suppose we were to use the 235-gallon tanks, which are bigger than four 55-gallon oil drums, with the best-combination 8% efficient compressor/motor system, to deliver one horsepower to run the blower for the rock storage in the Ark. Assuming an operating pressure range from 125 psi down to 80 psi (you can't use up all the pressure and keep the blower powered sufficiently), one tank will last less than two minutes and it would cost $270 per minute storage capacity for tank capital alone. For comparison, lead-acid batteries of equivalent energy delivery capacity cost less than a tenth as much ($17 per horsepower minute, initial capital). It should be noted though that with room for roughly tenfold improvement in air motor efficiency, and hence in effectiveness of use of air storage capacity, better equipment could change the whole economic picture.

What of future possibilities if we envision equipment not currently available? I have already indicated that the costs of the theoretical tank materials will vary roughly as pressure-times-volume capacity. The energy carrying capacity of a tank, assuming ideal recovery, is a somewhat more complicated function. The following table expresses theoretical energy carrying capacity divided by pressure-times-volume in order to indicate how performance/cost ratios might be expected to vary with design pressure:

Pressure, atmospheres (gauge)	1.00	3.00	5.00	7.00	9.00	11.00	13.00	15.00
Performance/Cost, arbitrary units	.28	.62	.84	1.00	1.13	1.24	1.34	1.42

Going up from the 7-atmospheres baseline case, we see a slight theoretical advantage in higher pressure, but the higher the pressure, the more difficult the thermal effects. Even when by-product heat pumping is taken into account, efficient high-pressure operation requires multiple stages of compression and decompression with inter-stage heat exchangers. (This applies to the 7-atmospheres range of current equipment.) This is the realm of complex industrial equipment, not simple wind machines.

Where geological reservoirs such as caverns, abandoned mines, or depleted natural-gas fields provide free storage, lower pressure operation with simpler equipment becomes feasible. There is a possibility that a compressed-air utility using pipelines, windmills, and natural storage might work. There was a municipal compressed-air utility early in this century in Paris. But at any practical pressure, thermal effects will be significant and will represent an efficiency loss wherever it is impractical to utilize the heat at points of energy production and the cold at points of consumption. Realistically, compressed-air storage for isolated small wind-energy systems seems out of the question.