Empowering Agriculture

ENERGY OPTIONS FOR HORTICULTURE

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Forward

Agriculture is the engine of development for many developing countries, often employing the majority of the population. USAID has actively promoted the integration of modern energy services with agriculture and horticulture around the world, to support social and economic development and to address the need for greatly expanded food production and food security.

Horticulture produces many high-value crops, especially fruit and vegetables, and often flowers for export.[2] Reliable, affordable supplies of electricity, thermal energy, and mechanical energy are essential to maximize productivity and quality of horticulture products. This guidebook was developed to assist USAID, its partners, and the developing country clients whom they serve with practical, application-specific information about energy supply options and ways to improve energy efficiency in horticulture operations.

For many developing countries, agriculture continues to be the dominant sector for employment and one with significant potential for growth as countries enter the global marketplace. Energy is key to expanding agricultural markets and trade by contributing to increased and diversified crop production, powering the chain of farm – to – shelf production, and transporting products to market.

Empowering Development

USAID Office of
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http://www.usaid.gov/our_work/economic_growth_and_trade/energy/index.html

1 Flowers are considered to be a horticultural crop. However, as only a minority of farmers in developing countries produces flowers to earn a livelihood, most references in this guide are to fruits and vegetables.

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Introduction and Overview

Purpose of this Guide

This guide has been prepared for use by USAID and its partners to assist local horticulture producers in identifying the electrical, mechanical (shaft horsepower), and thermal requirements for various stages of the horticulture process and to assist these producers in selecting suitable efficient technical options to meet those energy needs.

Horticulture, the growing of fruits and vegetables for local and more distant markets, involves the following steps:

- Land preparation
- Irrigation
- Planting and cultivation
- Harvesting
- Postharvest handling and packing
- Cooling and cold storage
- Transport
- Processing

The amount and the type of energy used in each of these stages reflect the type of horticultural product, scale of operations, financial resources of operators, availability of energy sources and resources, and availability of relevant energy technologies.

This guide provides data on technology acquisition costs, energy consumption, capacity, and effectiveness of technical options. Costs continue to evolve, and petroleum fuel prices are especially volatile as of this writing. For this reason, cost comparisons and cost-benefit calculations should be done each time a horticultural producer or marketer makes a decision about which technologies to use.

Structure of this Guide

The guide is organized by stages of horticultural production, covering irrigation and harvesting and post-harvesting operations. A separate section on biomass-based fuels looks at the opportunities to reduce fossil fuel requirements by utilizing renewable fuels. Each section identifies the general types of technologies and energy inputs, together with information about cost, energy requirements, capacity, and limitations. Technology Selection Criteria Tables associate types of technologies with the different types of horticultural operations as distinguished by size and capacity, economic resources available, location in relation to power sources and markets, and other factors. The detailed information in the tables clarifies technology options and the anticipated energy use and conservation results.

This guide covers a wide range of energy sources, from manual power to biomass and liquid biofuels to fossil fuels, machinery powered by grid electricity or by photovoltaic generation, and work performed by harnessing wind. The full range of producer scales is covered, from one-person operations serving a neighborhood using human-powered energy, to larger farms that truck cooled produce to urban markets.

This guide includes discussions of renewable energy technologies suitable for horticulture operations, from small-scale to large-scale operations. The guide also includes a brief discussion of small-scale local production of vegetable oils that can be used to fuel small diesel engines and gensets designed to run on these oils, and an overview of an emerging commercial technology for production of shaft horsepower, electricity, and process heat from biomass residues. None of these energy technologies is specific to horticulture. However, the dramatic increases in 2007-2008 in prices of petroleum products worldwide make renewable energy technologies increasingly attractive for agriculture and horticulture. Advantages and limitations of adapting renewable energy technologies to horticulture are discussed, and online resources are identified to provide further information on the costs and performance of these technologies.

Sustainability Issues and Criteria

Sustainability is defined in terms of reliable access to technologies and their spare parts and repair services, reliable access to fuels, cost-effectiveness, and management capacity. The management criterion is distinct from the others in that it involves characteristics of the producer. The ability of a producer to use energy and technology as assets, rather than having them turn into liabilities, is essential in sustainable adoption of these technologies.

Meeting horticultural users' technology needs in a cost-effective manner is particularly important. This guide emphasizes matching the capacities and costs of energy-consuming technologies to the capacities and resources of horticultural operations. The benefits of an efficient producer-technology match include minimization of debt and debt-related expenses, shortened amortization periods, reduction of waste from excess capacity, and, most fundamentally, the maximization of the enterprise's profitability and viability.

Equipment Issues

The guide discusses issues related to the availability of equipment, manuals, spare parts, repair services, and energy. When this guide was prepared, the prices for petroleum and petroleum-based refined fuels (gasoline, diesel, and kerosene) had exceeded US$100/bbl and had peaked at over US$140/bbl by early July 2008. The rapid run-up in prices affects both on-site operations and the price of transporting agricultural goods to market, compromising the cost-effectiveness of horticultural operations powered by gasoline and diesel fuel. Also problematic are the rising costs of supply inputs and the associated transportation costs of these materials. Technologies based on fossil fuels that made economic sense as late as the year 2005 may soon become, or already have become, prohibitively expensive. Users of this guide should pay particular attention to the most fuel-efficient technologies, and give careful consideration to technologies that minimize or avoid the use of fossil fuels.

Many of the technologies discussed in this guide involve equipment, parts, and fuels that must be supplied to production zones from outside. However, low-technology equipment such as treadle pumps often can be manufactured within a few dozen kilometers of production zones. Others, including brick-and-sand coolers and ventilated storage buildings, can be constructed on-site using materials that are made or sold locally. If the transport costs of equipment are embedded in the final retail price, this may favor local manufacture of simple technologies that involve only welding, masonry, wood working, and similar widely practiced trades.

Equipment supply chains: A condition for sustainable technology transfer is the availability of the necessary equipment, replacement parts, servicing know-how, and fuels within the usual travel range of users. These materials must be affordable for local agricultural producers. These conditions may not be met when equipment is supplied and paid for by entities other than the users, such as NGOs, bilateral assistance agencies, UN agencies, and other project sponsors. Stakeholders and sponsors should work together to assure reliable local supply of equipment (whether produced in country or imported), spare parts, tools, lubricants, and user guides in the local language(s) to avoid shutdowns in agricultural production or processing due to interruptions in the supply chains or missing information on the essential technology.

Sustainable technology availability means that there are sales points supplied by a chain of merchants reaching from the point of manufacture to the point where the technologies are purchased by users. The final purchase price includes the cost of manufacture as well as transport, commercial margins, taxes, and other charges involved in supplying the material to the user. In addition, purchased equipment and parts must come with enforceable after-sales warranties and service/repair arrangements. Service needs can be seriously compromised if donor agencies do not make appropriate provisions and only supply hardware.

Additionally, if there are several donors providing equipment, there should be a strong effort by the host country government to coordinate donor support and settle on one or just a few principal suppliers of equipment, to minimize the need for multiple manuals, multiple sets of tools for maintenance, repair, and replacement of parts, and the complexity of maintaining multiple sets of spare parts. Lack of coordination in this area creates serious challenges throughout the developing world to the uninterrupted operation and maintenance of equipment such as solar-powered vaccine refrigerators and small diesel generators for off-grid power generation.

Equipment manuals: It is essential that almost all equipment used in horticulture comes with user guides written in the local language(s). This important component of sustainability often is missing in donor-based equipment supply arrangements.

Spare parts: Equipment components must be readily available to replace broken or worn-out parts. The end user and equipment suppliers should identify the spare parts and tools that are required for rapid repair of key equipment. In some cases parts can be locally manufactured even if the machinery is imported. If repairs require specialized expertise, trained local mechanics are a vital link in the technology supply chain. Repair services and replacement costs may be paid either by users or by machinery suppliers under warranty agreements.

Energy supply issues: Both high petroleum fuel prices and potential fuel logistics problems have to be considered. In remote locations liquid fuels may not be commercially available and may have to be brought overland or by boat in small quantities from the nearest sales point. This often adds significantly to the prices horticultural producers pay for fuel. In many rural locations, fuel supplies are unreliable, which can result in significant and/or unexpected down times. If these interruptions occur at critical points in the production and commercialization cycle, such as irrigation or cooling of freshly harvested produce, an entire season's production can be lost.

In areas with unreliable fuel supplies, use of local energy resources often is advisable. These resources include human and/or animal energy for pumping, transport, and other parts of the agricultural cycle; locally produced biofuels such as Jatropha curcas oil as a partial or total substitute for diesel fuel; charcoal, wood, or agricultural residues (e.g., nut shells) for powering boilers and generators; and electricity from micro-hydro, wind, or solar power.

Fuel quality: Adulteration of fuels, whether accidental or deliberate, is a common problem in many rural areas. Fuel that is delivered in informal containers such as plastic jugs is likely to be contaminated by water and dirt. Filtration to remove solid particles is essential, but removing any excess water is difficult. As a result, motors may not operate efficiently, and mechanical breakdowns may be more common

Inadequate grid electricity: Electricity from the grid may be available and reliable in some locations. However, the presence of a local grid does not guarantee either the availability or quality of the electricity supply. If there is poor control of voltage or frequency, motors and electronics can easily be destroyed by surges and spikes. In areas with unreliable electricity supply, it can be more cost effective for horticultural production processes to be powered by some mix of diesel and propane generators, wind or solar power generation, biomass-powered gensets, and micro-hydro power. For small-scale, high-value uses of electricity, such as for computers, telecommunications, and electronic controls, the addition of uninterruptible power supplies is highly recommended as a cost-effective option. These power supplies combine batteries and inverters to assure reliable and very high quality electricity from poor quality power grid sources. In assessing the full relative costs of various sources of electricity, the cost impacts of poor quality electricity and supply outages from the grid may lead producers to install on-site generators even if the cost of electricity from on-site units is well above the local grid price.

Cost Planning and Cost-Benefit Analysis

In addition to having reliable supplies of equipment and energy, horticultural production must be financially sustainable. It is recommended that the following strategies be considered carefully as a necessary planning step in any investments for horticulture activities:

- The technology to be adopted should be the minimum size to cover the present and projected needs of an enterprise (i.e., appropriate scale);
- The technology should be the lowest-cost option in terms of purchase price, maintenance, and routine operation to cover the needs of an enterprise;
- The amortized purchase cost and recurring maintenance and operation costs must be justified by the incremental income generated.

Excess power and energy supply capacity generally result in excess costs and reduced economic viability. For example, if a motorized pump has the same capacity as four manual pumps, a small horticultural operation may find it more cost effective to meet its water supply needs with a few manual pumps rather than a motorized pump.

A cost-benefit comparison should be conducted for the life of the technologies under consideration, to select the most appropriate option. Competing technologies should be compared in common terms, such as kWh/MT (kilowatt hour per metric ton) or $/MT of irrigated, transported, cooled, or packed produce. Trade-offs may involve higher costs for the purchase of relatively high-technology equipment versus lower purchase and energy costs and higher labor costs for a lower-technology version, taking into account their relative effectiveness. Low-energy post-harvest cooling methods may result in higher losses than mechanical refrigeration, but those losses may be more than offset by energy savings. Rising fuel prices may push the energy/labor trade off towards lower-technology, more labor-intensive activities.

Even selection of the most appropriate technology with the lowest cost per unit output does not guarantee economic sustainability. If the bottom line is still negative, then conditions are not favorable for commercial horticultural production in a given location with existing input supplies, market access, producer prices, and other factors of production.

Management Issues

With larger-scale operations and the use of more complex technologies, greater managerial expertise is required to manage the operation. Available management capacity needs to be taken into account when selecting technologies.

Micro-enterprises, particularly those originating in agriculture, often start out with limited management expertise. One-person or family-run businesses tend to operate without a high degree of experience in personnel management, detailed financial planning, or technology sophistication. When enterprises adopt “next-step” technologies, such as drip irrigation networks or mechanical sorters and coolers, greater training and skills are required. These technologies generally can be managed by owner-operators if they have the right training.

Management challenges arise as an operation grows larger, requires a larger and more diversified labor force, and serves a broader and more demanding group of clients. The greater scale and complexity of larger operations demand human resource expertise, financial planning, marketing, full-time technological support, computer and internet capabilities, and other management skills. Ideally, a growing operation trains its existing personnel and hires individuals with other necessary expertise as its skill needs increase.

Horticultural cooperatives, whose personnel generally consist of their farmer members, are one form of production unit that is often plagued by management constraints. If a cooperative aspires to produce on any scale, access distant and sophisticated markets to command the highest prices, and spread its production throughout the year, it cannot rely solely on the farming expertise of its membership. The cooperative needs to be able to hire employees with relevant training, and some of the members will need to acquire business management skills, particularly in the areas of financial planning, professional marketing, shipping and conservation techniques, the adoption of multiple technologies, and new and specialized agricultural training.

When a cooperative purchases machinery, for example, a planner must also set aside money for repairs and maintenance and eventual replacement. A planner, be it an original employee or cooperative member with training or a person hired for the purpose, is the one to study the relative economic efficiency of different technologies prior to the decision to purchase, and the person responsible for ensuring that the operation will remain profitable under its new production model.

No discussion of rural electricity needs can ignore the potential for photovoltaic (PV) panels. However, a major obstacle to the widespread use of photovoltaic systems for rural electricity services is their initial cost. Diesel and kerosene-powered engines, pumps, and generators have much lower initial capital costs than their PV counterparts, but the fuel costs have become extremely expensive. A modern 10 horsepower (HP) single cylinder efficient and reliable air-cooled diesel engine[2] retails for about US$2,000, or roughly $200 per kilowatt, and can be operated for 6 to 12 hours per day. A PV system with comparable output would require 20 to 30 kWp capacity and would cost on the order of $25,000. At US$1.00 per liter of diesel fuel, the fuel cost component of electricity from small (10 to 20 HP) diesel engines is $0.40 to 0.60 per kWh. This is comparable to the cost of electricity from small PV systems. However, the latter cost reflects low-interest, long-term financing of the PV systems. Moreover, if a horticulture operation cannot afford electricity prices of $0.50/kWh, it doesn't matter if the electricity source is a diesel engine or an attractively financed PV system.

The average retail price[3] of PV panels (125 watts or larger) in 2008 has been just under US$ 5per rated peak watt, with some modules as low as $4 per peak watt from a few U.S. retailers. Depending on the electricity application, other equipment will be needed such as batteries, charge controllers, support structures for the panels, and secure ventilated containers for the batteries. The cost of a complete system, not including the end-use applications (e.g., water pump, lighting, fans, etc.) can easily be $8 to $10 or more per peak watt.

Industry observers[4] do not expect any decline in PV panel costs and prices for several years, perhaps not until after 2010. For several years the annual 30% growth in the markets for PV panels has resulted in a supply bottleneck for solar-grade silicon. This has caused module prices to rise. The supply problem is expected to disappear within the next several years, but the prices for PV modules and systems may not decline, since these are determined by market factors, not just production costs. Other components of PV systems, such as batteries and controls, are not expected to experience significant future cost reductions.

Capital cost challenges involving renewable energy sources tend to be far greater in many developing countries than in OECD countries. Developing country governments often tax imported PV equipment (a 5 to 20% rate is not uncommon). This is in contrast to applications in many OECD countries, where there are often tax breaks and other financial incentives for businesses and homes to install PV systems.

For small-scale and medium-scale commercial horticulture operations, the use of PV systems involves installations sized to provide sufficient power for pumping water from a deep well, or for running an electric motor-powered dryer, for example. Such installations are almost exclusively financed by donors without expectation of capital recovery, and tend to cost at least $10,000, and often $30,000 to $50,000. In the water-pumping application the use of a photovoltaic array to power a deep well submersible pump is often the most practical application, since batteries are not required. The system pumps to a storage reservoir or water tower when the sun is shining, thereby storing water rather than electricity. A high yielding well with a sufficiently large photovoltaic array may be used to provide irrigation for horticulture. Alternatively, a large PV array could power an electric motor-driven shallow lift centrifugal pump from a surface water source to irrigate a relatively large (several hectare) horticultural farm or farms. In both cases, a battery-charging station may advantageously be connected to the photovoltaic panel array to enable villagers to use electricity in their homes, and the added electricity sales used to help defray the cost of the installation.

2 See, for example, the Hatz 10 HP air-cooled diesel engine. www.northerntool.com

3 Solar Retail Price Environment (August 2008). The monthly surveys covered over 70 module suppliers and over 500 different module types and models. Companies in the following countries are represented in the surveys: United States, Germany, United Kingdom, South Africa, Brazil, Mexico, Australia, France, Switzerland, Greece, Korea and Canada. http://www.solarbuzz.com/Moduleprices.htm

4 Peter Lorenz, Dickon Pinner, and Thomas Seitz (June 2008). The Economics of Solar Power. The McKinsey Quarterly. McKinsey & Company.

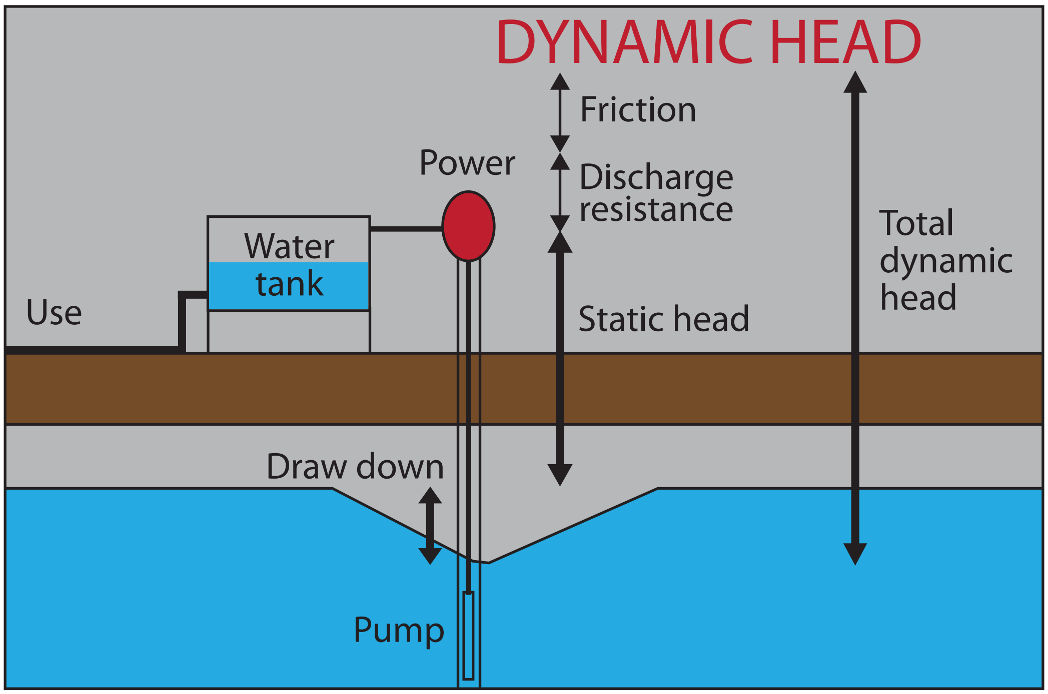
Chapter 1: Irrigation

"Irrigation" refers to the pumping and distribution of water for growing crops, including the use of water storage, where appropriate. The energy demand for irrigation purposes is the energy required to lift water by pumping from surface sources, such as ponds, streams, or canals; or from below-ground sources using open wells or boreholes. This water typically is pumped to surface canals, reservoirs, or elevated tanks.

The energy demand for water lifting depends on the head (the vertical distance from the water source to the field in meters), multiplied by the volume of water to be raised in cubic meters (m^3). The energy demand may be larger than indicated by this simple calculation, due to friction and leaks in the distribution system (the "dynamic head" is the static head or vertical lift plus the additional lift associated with frictional losses and water drawdown (see Figure 1)). Pumping energy needs are typically expressed in units of m^4 (meters to the fourth power).

Decisions about energy and irrigation should be made in a stepwise fashion, first understanding the irrigation system needs for a given context, then understanding the various pumping technologies available, and, finally, assessing which power sources are possible, desirable, and locally available to provide the necessary energy for that system.

Figure 1 Definition of Dynamic Head for Water Pumping



Source: Winrock International

Choosing the Right Irrigation Technology

Selecting the type of irrigation water distribution system to be used is the crucial first step in understanding the pump technology required and the associated energy and power source requirements. Which irrigation system is most suitable will depend on several factors including the crop(s) cultivated, climate, location, scale/area of agricultural production, quantity of water required over time, system cost, access to capital, local agricultural workers' technical capacity, and the availability of equipment, including local maintenance, repair, and equipment replacement capabilities. Irrigation systems differ in their peak and average water requirements, the need for water storage (e.g., tanks, cisterns), and the ultimate need for pumping and energy. Where small producers (those cultivating less than two hectares) are targeted, the more expensive irrigation technologies may only be accessible through membership in producer companies or cooperatives and farmers' associations, where the latter have sufficient ability to raise capital, as well as having the management capacity for technology adoption, operation, maintenance, and replacement.

The most common irrigation technologies in use include the following:

- **Surface Irrigation:** In surface irrigation systems water moves over and across the land by simple gravity flow in order to wet and infiltrate the soil. This approach is often called "flood irrigation" when the irrigation results in flooding or near flooding of the cultivated land. Historically, this has been the most common method of irrigating agricultural land. Where water levels from the irrigation source permit, the levels are controlled by dikes, with simple soil dams to control water levels. In some cases, water in ditches is pumped or lifted by human or animal power to the level of the field. Advantages of this approach are its low cost and simple technology. Disadvantages include the inefficient use of water and potentially high evaporative losses, as well as long-term problems arising from the increased soil salinity that can result in some areas when fields are routinely flooded through this type of irrigation.
- **Sprinkler / Aspersion Irrigation:** Sprinkler or overhead irrigation involves piping water to one or more central locations within the field and distributing it by high-pressure sprinklers or guns. Numerous system types exist, including center pivot, rotating, traveling/water-reel, lateral move/side roll/wheel line, etc., each with a different cost and amount of labor required to operate the system. Advantages include the potential labor savings and more efficient use of water than in surface irrigation. These systems can be expensive and require technical capacity to operate and maintain.
- **Drip Irrigation / Micro-irrigation:** Drip irrigation, also known as trickle irrigation, delivers water directly at or near the root zone of plants, drop by drop. This method is a highly water-efficient method of irrigation, since evaporation and runoff are minimized. Because of reduced and more uniform water use, fewer chemical inputs are generally required as well. Savings in both water and labor expand the irrigable areas with any given pump by a factor of as much as two. Lower water pressures and energy use are required compared to some other automated systems, but it can be difficult to regulate pressure in sloped sites. System maintenance can be higher than other irrigation systems, especially the efforts required to filter water to remove particles that may clog the tubes. Drip irrigation can also be a fairly costly system to install, especially the higher end automated technologies, although some very low cost models do exist as well (which require much more labor). (See Figures 2 and 3 for examples of drip irrigation).
- **Sub-irrigation / Seepage Irrigation:** This method of irrigation delivers water to the plant root zone from below the soil surface and the water is absorbed upwards. The excess may be collected for reuse. Sub-irrigation is used to grow field crops such as tomatoes, peppers, and sugar cane in areas with high water tables, as well as commercial greenhouse operations. In field crops, these systems often are located on permanent grasslands in lowlands or river valleys, with a system of pumping stations, canals, weirs, and gates in place to control the level of the water table. Greenhouse sub-irrigation has been growing in popularity, and has advantages including water and nutrient conservation, in addition to potential labor cost savings. The up-front investment required and the sophistication of the technology are high, however.
- **Manual Irrigation:** Systems using buckets or watering cans have low requirements for infrastructure and technical equipment but need high labor inputs. This type of system can be found in smallholder agriculture, market gardening, or peri-urban agriculture.

In general, the scale of production and costs of the technology will drive the decision about which irrigation approach to use. For the smallest production units, manual technologies provide the necessary services at the lowest up-front and operating costs. Treadle pumps may be attractive for small-scale farming (less than one ha). The size, cost, and capacity of suitable technologies increase along with the scale of production. The following table provides some guidance for the selection of irrigation technologies based on key criteria such as production scale, energy source, and budget.

Table 1 Comparative Analysis of Irrigation Methods

Irrigation Method	Irrigated Area	Water Requirements	Energy Requirements	Capital Cost	Operating Cost
Manual	<0.5 ha	Low to High*	Low (manual only)	Low	Low to Medium***
Surface / Gravity fed	Unlimited	High	Low (manual only)**	Medium	Low
Sprinkler	Unlimited	Medium	High	High	High
Drip / Micro-irrigation	Unlimited	Low	Medium	High	Medium

* The amount of water used in a manual system will depend on the technology used for distribution.
** In some systems, pumping may be required at certain points in the system.
*** Operating costs will depend on local labor costs and the type of manual irrigation technology used.
Source: Winrock International

Figure 2 Solar-powered Drip Irrigation System in Chile

Photo Credit: GTZ

Figure 3 Drip Irrigation System

Photo Credit: Steev Lynn

Choosing the Right Pump Technology

There are a wide variety of pump technologies available for irrigation, but not all are appropriate for every irrigation system type. Among other things, pumps differ in their pumping approach, size and capacity, the type of water source they are suitable for (groundwater or surface water), the scale/area of irrigation possible, their cost, and technical complexity.

Pumps can be classified into two broad categories: manual or motorized (mechanized):

Suction Versus Pressure Pumping

Pumps lift or move water in two basic ways: suction between the pump and the source; or pressure between the pump and the water storage and/or distribution system.

Suction pumping is less efficient than pressure pumping, and is subject to a theoretical depth limit of 9.8 meters. [The pressure of a 9.8m column of water equals ambient air pressure.] Human-powered or motorized piston pumps are generally limited to no more than 8 meters of suction head, while gasoline engine-powered centrifugal pumps may reach only 6-7 meters.

Pressure pumping is not subject to the natural physical limits of suction pumping. A pressure pump's ability to push water upwards is determined by its pressure rating and speed. As a rule, the power required of a pump is proportional to the lift and to the flow of water that is needed. For each horsepower rating, small pumps are normally capable of lifting approximately 10 cubic meters per hour 10 meters high. In addition, flow resistance or pressure loss in the distribution piping must be added to the gravity or vertical head when calculating the total lift.

Manual Technologies

A range of hand- and foot-operated pumps is available for small-scale irrigation. Most of these operate entirely or partially on suction. Single-cylinder submersible hand- and foot-operated pressure pumps, as well as rope-and-washer pumps, are widely used, but their limited output generally confines their use to small-scale potable water supply.

Two-cylinder manual and treadle suction pumps can reach depths of 7 to 8 meters for irrigation (see Figure 4). Their output is approximately 7.5 m3 per hour for two-person foot pumps at depths of up to 5 meters, with output decreasing to 4 m3/hr at 7 meters depth. A hand-operated two-cylinder irrigation pump can provide 4 to 5 m3/hr over the same range of depths, but its physical demands limit the time it is used, lowering its effective daily output capacity. Low-lift treadle pumps with large diameter cylinders, used for surface water sources or very shallow wells of 2-3 meters, have higher capacities, in the range of 10-15 m3/hr.

Foot-operated treadle pumps have higher outputs than manual versions because they use the weight of the operator's body as a counterbalance, and take advantage of the greater strength and endurance of lower-body muscles relative to the upper body. For this reason, they can be operated for longer periods than hand pumps, consequently with higher daily outputs, and may be a more appropriate solution for the considerable irrigation demands of horticultural crops (see Case Study #1).

Case Study 1: Treadle Pumps in Niger

Context: Smallholder producers in 2007 in the Zinder and Maradi regions in Niger (USAID-funded West Africa Water Initiative, implemented by Winrock International).

Problem statement: Mr. Garba Yerima, from the Magaria area of Niger, was a farm laborer in Nigeria. He had long wanted to establish his own production unit back home, but water, and the labor to raise and distribute it, is one of the major limiting factors to horticultural production in Niger. The pumps generally available are too expensive for small for start-up vegetable gardens.

Background: Annual rainfall amounts in Magaria are generally between 500 and 600 mm. Water is traditionally raised from wells by laborious manual methods, constraining garden sizes to around 0.10 to 0.20 hectare per person in typical situations.

Technology selected to address the problem: Mr. Yerima used the savings from his Nigerian job to purchase both a treadle pump and a hand-augured tube well for the debut of his own garden. Local welding shops were trained by Winrock International to manufacture treadle pumps, which are operated by foot and body-weight action and can pump up to about 7 m^3 of water from wells as deep as 7 meters. Depending on soils and distribution systems, this is sufficient to irrigate about 0.5 ha of vegetables. Being locally manufactured, the pumps are also affordable to small growers, costing the equivalent of about $50 (not including pipes). The tubewell cost the equivalent of approximately $130. All told, the investment was about $200.

Results: Mr. Yerima's new garden covers approximately 0.5 ha. With the earnings from his pump and well, he reports that he is able to feed his family. In Niger, first-time treadle pump users reported doubling or tripling their irrigated areas and increasing their incomes by an average of $200 per season. This is enough to recover the entire investment cost during the first growing season. Over the expected five-year life of a pump, the increased earnings can reach approximately $1,000.

The treadle pump almost instantly raises producers' standards of living and improves the nutritional supply in a given area. Given the greater cash availability due to pump use, many small horticultural producers who have the available land choose to add a second or third treadle pump and hire labor to further expand their production. Beyond that point, some producers then step up to the next level of technology, a diesel or gasoline-powered pump that can irrigate several hectares.

Plot extension immediately following treadle pump purchase (Niger)

Photo Credit: Samuel Tanon, Winrock International

Motorized Technologies

Shallow water pumps

The most common motor pump used in small-scale horticulture is the centrifugal surface-mounted pump with a head limit of 6 meters in practice (see Figure 5). This mechanical engine-powered pump, usually 3.5 to 5 HP and gasoline powered, has an output in the range of 20-50 m^3/hr. These pumps cost from $100 to $450. Operating costs vary according to the type of fuel/energy used (e.g., an average of 0.4 L per hour of gasoline). Diesel engine pumps, in contrast, are typically at least 10 HP, and therefore of greater capacity than typical gasoline engines used to power irrigation pumps, and consume approximately 2 L per hour.

Larger, more expensive mechanical centrifugal pumps also exist, and have greater output capacity. Differing widely in terms of quality, a 5 HP pump manufactured in India or China costs from $200 to more than $700, with an output of approximately 40 m^3/hr. Fuel consumption varies depending on motor size, output, and pumping head. Larger pumps, including those powered from vehicle engines, are capable of delivering several hundred cubic meters per hour from shallow wells and surface sources.

Figure 4 A Simple Treadle Pump

Photo Credit: USAID Photo Gallery; http://gemini.info.usaid.gov/photos/displayimage.php?album=858&pos=12

Figure 5 Small Mechanical Centrifugal Pump

Photo Credit: Winrock International

Deep water pumps

Pumping from greater depths requires submersible pumps, which are installed below the water level in wells to push water upward by means of pressure (see Figure 6). Submersible pumps must always be used for depths beyond 10 meters and for larger-scale irrigation operations (greater than 4 hectares). A 3 HP submersible pump can reach a depth of almost 40 meters and pump at capacities of approximately 9 m^3/hr.

Motorized submersible pumps may be sized to meet the needs of farms of almost any size. Submersible pumps typically cost in the range of $600 to several thousand dollars. Installation may require far higher total costs, depending on the need for well drilling and installation, pipes, extension of electric wires or installation of off-grid generation equipment where applicable, construction of reservoirs (tanks), and other factors. Total cost of the complete system can easily reach or exceed several thousand dollars, depending on well depth, location, and additional equipment requirements.

Table 2 presents guidance regarding the most appropriate type of water pump, given the area to be irrigated combined with the water table depth. Table 3 provides information regarding the relative cost of each of the major pump types discussed.

Figure 6 Submersible Electric Pump

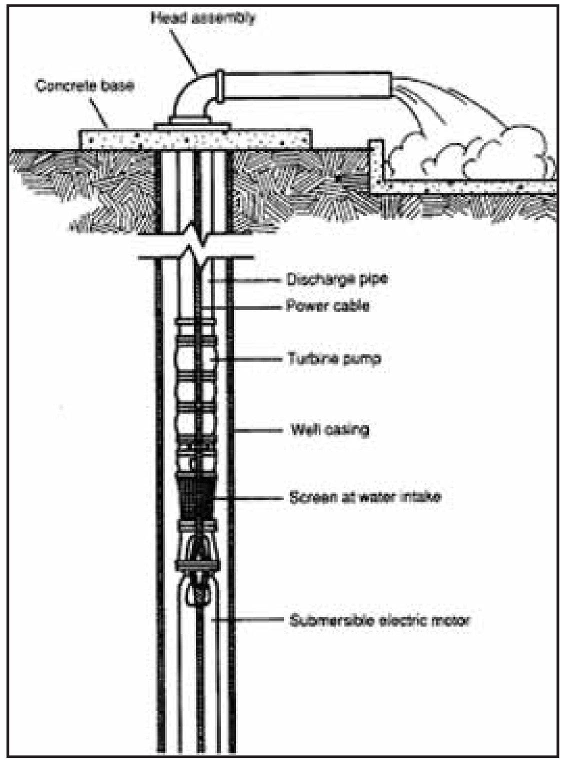


Photo Credit: Thomas F. Scherer AE-1057, April 1993, North Dakota State University.
http://www.ag.ndsu.edu/pubs/ageng/irrigate/ae1057w.htm

Table 2 Water Pumping Options for Different Irrigated Areas and Water Depths (for irrigation methods that require pumping)

Water Depth / Irrigated Area	Water Table = < 8 m	Water Table = > 8 m
<2 ha	Manual Pump: hand pump treadle pump (~1 pump/0.5 ha) Motorized Pump: 3-5 hp mechanical pump <5 hp electric pump	Motorized Pump: 3-5 hp mechanical pump (submersible only) <5 hp electric pump (submersible only)
2-4 ha	Motorized Pump: >5 hp mechanical pump >5 hp electric pump	Motorized Pump: 3-5 hp mechanical pump (submersible only) <5 hp electric pump (submersible only)
>4 ha	Motorized Pump: >5 hp mechanical pump >5 hp electric pump	Motorized Pump: 3-5 hp mechanical pump (submersible only) <5 hp electric pump (submersible only)

Source: Winrock International

Table 3 Typical Capital Cost Ranges for Pumping Technologies

Capital Budget for Pumping	Available Options
Under $100	Manual and treadle pumps
$200-$600	Mechanical suction pumps – 3-5 hp; manual or treadle pumps
$600-$2000	Mechanical suction pumps – >5 hp; distribution pipe networks
>$2000	Submersible electric or mechanical pumps for deep borehole wells

NOTE: Cost figures for borehole wells, distribution systems, irrigation technologies, etc. cannot be provided here because they can vary by a factor of two to ten, depending on well depth and aquifer material, extent of the distribution system, local pricing of services and supplies, and other parameters specific to individual operations and locations. Consequently, the price ranges given here are for the pumps only.

Source: Winrock International

The following table compares technical and cost aspects of various water pumps:

Table 4 Comparison of Water Pumps

Pumping Technology	Purchase Price	Energy Use	Maximum Head (m)	Output at 7m (m3)**	Pumping Cost per m^3
Treadle pump	$100	$0.25/h labor	7	4	$0.06
Manual 2-cylinder suction pump	$120	$0.25/h labor	7	4	$0.08
Manual rope & washer	$200	$0.38/h labor	20	12	$0.32
Diesel suction pump	$700	0.4 L/h	8	40	$0.02
Gasoline centrifugal pump	$400	0.4 L/h	6	19	$0.04
Submersible electric pump*	$2,800	2.24 kw	70	9	$0.14
Submersible diesel pump*	$2,800	1 L/h	70	9	$0.14
Solar pump*	$2,736	0	70	1.6	$0.06
Wind electric pump*	$4,000	0	240	1	$0.19

*Includes pump but excludes pipes
**Assumes a 7m well possesses the recharge rates sufficient to supply the outputs indicated
Source: Winrock International

Other Table 4 Assumptions

Life of manual suction pump in m^3	9,000	Pumping 4 m^3/h x 3 h/d x 150 d/y x 5 yrs
Life of treadle pump in m^3	18,750	Pumping 5 m^3/h x 5 h/d x 150 d/y x 5 yrs
Life of diesel suction pump in m^3	54,000	Pumping 40 m^3/h x 3 h/d x 150 d/y x 3 yrs
Life of solar pump in m^3	45,000	Pumping 1.5 m^3/h x 10 h/d x 300 d/y x 10 yrs
Life of wind pump in m^3	21,000	Pumping 1 m^3/h x 10 h/d x 300 d/6 x 7 yrs
Diesel fuel cost $/L	$0.77	In Central America 2007
Gasoline fuel cost $/L	$1.00	In Central America 2007
Labor cost $/8 hr day	$2.00	In West Africa 2007, unskilled
Electricity cost $/kwh	$0.35	Estimate; varies by country

Sources: FIELD, http://www.fieldresource.org; Subaru-Robin Pumps http://www.subaru-robin.jp; Notibiz Portal de Finanzas, http://www.notibiz.notiemail.com/noticias.asp?leng=es&id=1130; W.D. Moore & Co., http://www.wdmoore.com.au/SolarSystems; Intergovernmental Authority on Development/Energy for Sustainable Development, http://igadrhep.energyprojects.net/Links/Profiles/WindPumps/TechProfile.htm

Choosing the Right Energy Source

Different pump technologies are often flexible in the type of energy source that may power them – e.g., submersible pumps exist that may be powered by a hand lever, a merry-go-round, a gasoline-powered mechanical pump, an electric pump connected to the power grid or to a solar panel or a wind electric generator.

Following is a brief list of the different energy sources available for motorized pumping, and the definition and characteristics of each.

Fossil fuels: Fossil fuels are employed to power motorized pumps, either through generators that create electricity,[5] or by transmitting power to the pump through a drive belt and vertical rotating shaft. In addition, some submersible pumps (i.e., progressing cavity pumps) operate by direct displacement, like piston pumps. These pumps tend to be more expensive but also more efficient than centrifugal pumps. Biofuels produced from a variety of sources may also be employed to power many of these pumps.

Figure 7 Solar-powered Electric Pump

Photo Credit: SC Solar, Inc., Rock Hill, SC

Solar energy (photovoltaic): Solar pumps are electric pumps powered by electricity produced from photovoltaic (PV) panels. A solar-powered DC submersible pump reaching a depth of 50 m can pump 2.7 m^3/hr. Installing this type of pump costs from $2,700 to $10,000, but there are fewer maintenance costs than a combustion engine-driven system, and the system may last 10 years rather than a few years (or even less). The life cycle cost of a solar-powered pump may compare favorably with an engine pump, factoring in the costs of fuel, lubricants, and spare parts. The capital cost of the solar pump, its susceptibility to theft of solar panels, and unfamiliarity to local mechanics can be impediments to their commercial use in some areas. Figure 7 shows an example of a solar-powered pump system.

For performance, cost, operating conditions, and availability data for PV water pumps, see the Solar Living Source book (2008).

Wind energy: Wind may be used to power both mechanical and electric pumps. Mechanical wind-powered pumps use reciprocal non-motorized submersible pumps, rather than electric centrifugal ones, and require a minimum wind speed of 2.5 m/s, with optimum performance requiring a wind speed of at least 4 m/s. Capacity is much lower than for motorized centrifugal pumps, in the range of 1 m^3/hr at depths of 20 meters or more. At this rate, even manual potable water deep-well pumps are competitive with windmills. Installation costs, including well drilling, windmill construction, pipes, pump, and other costs, range from $1,000 to $4,000, depending on whether the equipment is fabricated locally or imported.

One advantage of mechanical wind pumps is that they can pump day or night as long as wind blows, and can be used independently of electricity or fuel supplies. A disadvantage is that they must be located directly above the well, a location that may not be optimal in terms of local wind resources. At such low output, wind pumps are appropriate in windy areas without other sources of power, and only for small irrigable areas.

Wind electric turbines convert the kinetic energy of the wind into rotational mechanical energy that drives a generator to produce electricity. Windmills are placed for optimal wind conditions, providing greater siting flexibility, in addition to facilitating electricity production for other uses.

5 Note that all electric pumps, regardless of energy source, can be controlled by automated signals, such as float or pressure switches, which allow them to pump at any time of day or night. This effectively raises their daily capacity to over 200 m^3, whereas a non-electric motorized pump controlled by a human operator is limited by the number of hours worked.

One of the priority applications is for pumping water for irrigation and potable water supply. Water-pumping applications generally make use of wind turbines with rated output between 1 kWe and 10 kWe. A wide variety of small wind electric turbines are commercially available, with rated outputs[6] ranging from a few tens of watts to 100 kilowatts, used throughout the world to provide electricity in locations where alternatives are not available or are too expensive or difficult to provide. Typical modern small wind tur-bines have only three moving parts, are designed for operational lives of 20 to 30 years, and are designed to operate for several years before routine maintenance is required.

Hybrid systems: Small-scale hybrid power systems, also a mature technology, are used worldwide. By combining solar and wind energy sources, hybrids can provide a high availability of electrical supply without the need for a backup generator. These small hybrid systems are easy to ship and very easy to install; no special tools or concrete are required. The wind turbine and tower can be assembled on the ground and tilted up using a hand winch. A $6,000 1.2 kW hybrid system can typically supply 3-5 kWh per day of 220 VAC, 50 Hz power.

The following is a list of several considerations to be factored into the selection of an energy source to power the pump selected for irrigation. These include:

Local power source availability and reliability: If the local electrical grid is accessible nearby, the availability, quality, and reliability of electricity supply will determine the practicality of using grid power. If the grid is unreliable, with brownouts and blackouts during the seasons when water is needed, produce losses may be substantial, and other energy sources for pumping may be more attractive or even essential – either as a primary source or a supplemental source. Most commonly, those options include gasoline, diesel, kerosene, or biofuel-powered pumps. Even in this scenario, if fuel supplies are unreliable, fuel quality is poor, or costs extremely high, the usefulness of fossil fuel-powered mechanical pumps will also be compromised. Under certain conditions, solar electric water pumping and wind electric water pumping may be technically and economically attractive. For relatively small farming areas (several hectares or less), solar and wind pumping may be especially attractive if reliable sunlight and/or wind resources are available when high pumping levels are needed. Where there are strong winds or long daylight hours during the periods in which maximum irrigation is needed, these may be effective stand-alone options. Having reliable diesel or kerosene backup to generate electricity for electric pumps can assure continuity of water pumping and irrigation in areas where sunlight/wind are less predictable.

Local technical capacity: The local availability of skilled operators and repair personnel for a given type of pump (and its power source) is a critical factor when selecting a power source/energy technology. Renewable technologies such as solar and wind systems may be imported, but locating spare parts as well as skilled personnel to address maintenance issues may prove challenging. In many countries even fossil fuel-powered pumps can fail within months due to the lack of local personnel trained in pump operation, maintenance, and repair, and/or due to the lack of suitable tools and spare parts.

Affordability: Both initial capital cost as well as ongoing operations and maintenance costs of each energy source technology should be considered. Manual pumps are relatively low cost in terms of both capital investment and operations/maintenance costs. Fossil fuel-driven motorized technologies are in the mid-range of capital costs, and have medium to high operations costs. Electric motorized technologies are about the same in terms of capital investment, and have variable operating costs, depending on the local price of electricity. The affordability of expensive solar and wind power technologies is largely limited by the availability of up-front capital, but ongoing costs are very low. The economics of solar pumping can be enhanced by identifying other uses for excess solar-generated electricity when not needed for irrigation, including charging batteries and grinding and milling of grain.

Security requirements: All pumping/irrigation systems, regardless of energy source, need to be protected from theft or vandalism. Solar panels are very expensive, and particularly prone to theft, as they are valuable both for illegal sale and for the electricity they produce. Widespread theft of PV panels in many countries has often limited their use, even when they are technically and economically suitable for the pumping and irrigation requirements for which they were purchased.

6 The range of 10 watts to 100 kilowatts of rated peak generating capacity is the definition of "small" wind technology adopted by the American Wind Energy Association (AWEA).

Table 5 below presents a summary of conditions to keep in mind when considering different energy sources of agricultural irrigation pumping.

Table 5 Energy Sources for Pumping Alternatives and Limiting Conditions

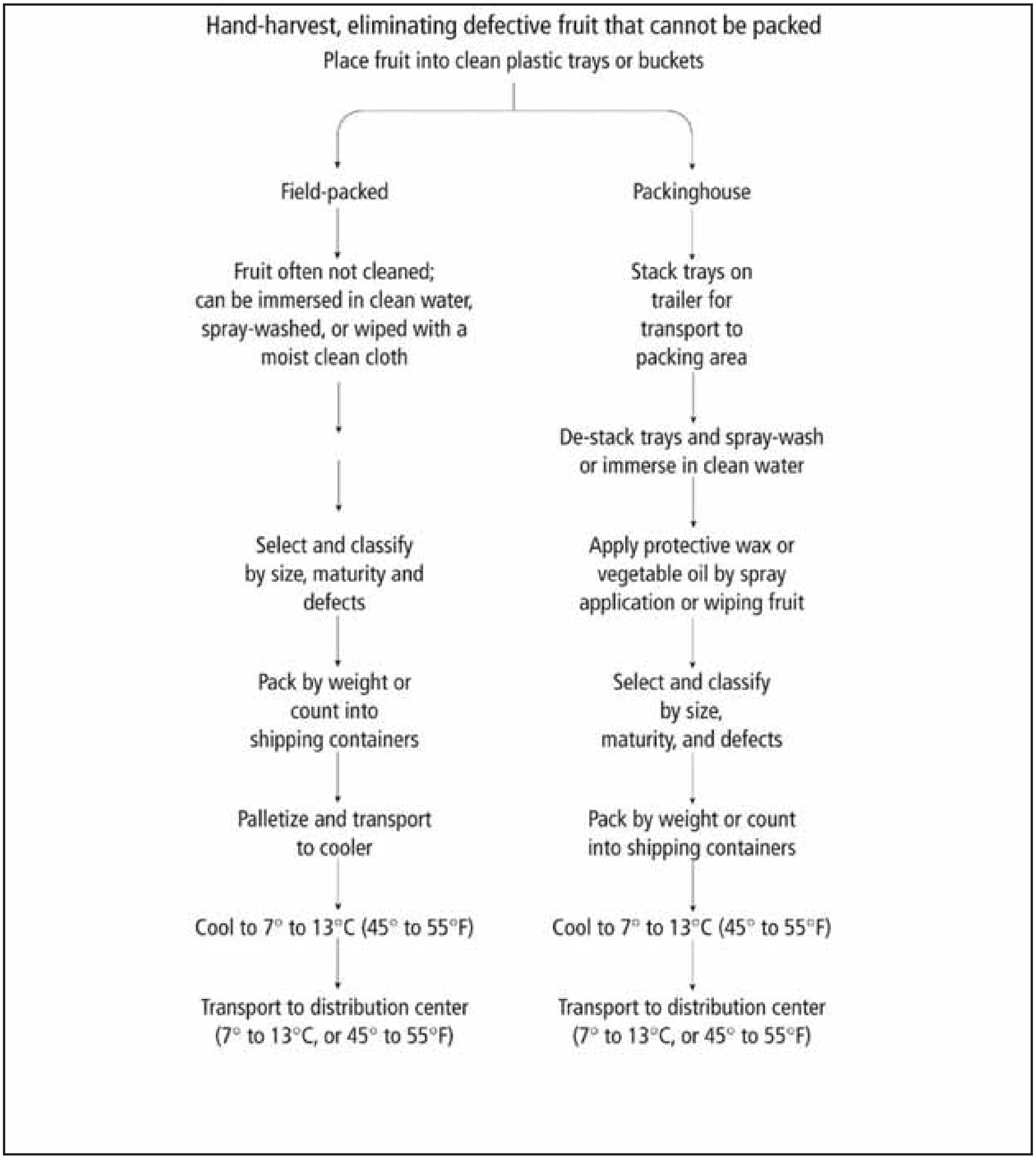
Type of Energy	Limiting Conditions
Manual	Requires both small scale of operations and adequate local labor force.
Gasoline	Fuel, repair services, and spare parts must be readily available, and these costs must not infringe seriously on profitability.
Diesel	Fuel, repair services, and spare parts must be readily available, and these costs must not infringe seriously on profitability. These pumps are generally not portable, so permanent installation must be possible and cost-effective.
Grid Electricity	Requires grid connection; local electricity costs must not infringe on profitability. However, the availability, reliability, and quality of local electricity supplies will also determine the desirability of this energy source. Poor power quality (including low voltage, voltage spikes, and harmonic distortion problems) will burn out pump motors; unreliable electricity supply may jeopardize crops.
Photovoltaic	Requires ample sunlight; attractive if financing is available and the initial cost can be amortized by earnings on produce.
Wind, Mechanical	Requires the availability of local maintenance and repair facilities able to respond quickly to mechanical failures. Adequate wind speeds must be present at the location of the wells.
Wind	Requires good wind resources during periods when pumping is needed. Applicable where the earnings on even very small irrigated areas can justify the initial capital cost, and where manual energy on this small scale is not available. Wind/diesel hybrid equipment may have lower annualized costs and greater reliability than either wind or diesel pumps alone.

Source: Winrock International

Chapter 2: Harvesting and Post Harvest Operations

Like other parts of the agricultural cycle, harvesting and post-harvesting operations involve energy use. This section provides information on the energy requirements for the various stages in harvesting and post-harvest operations.[7] The sequence of processes involved in horticulture is exemplified by the flow diagrams in Figures 8 and 9, which describe post-harvest handling of immature fruit and vegetables such as summer squash, eggplant, and cucumbers; and post-harvest handling of melons.

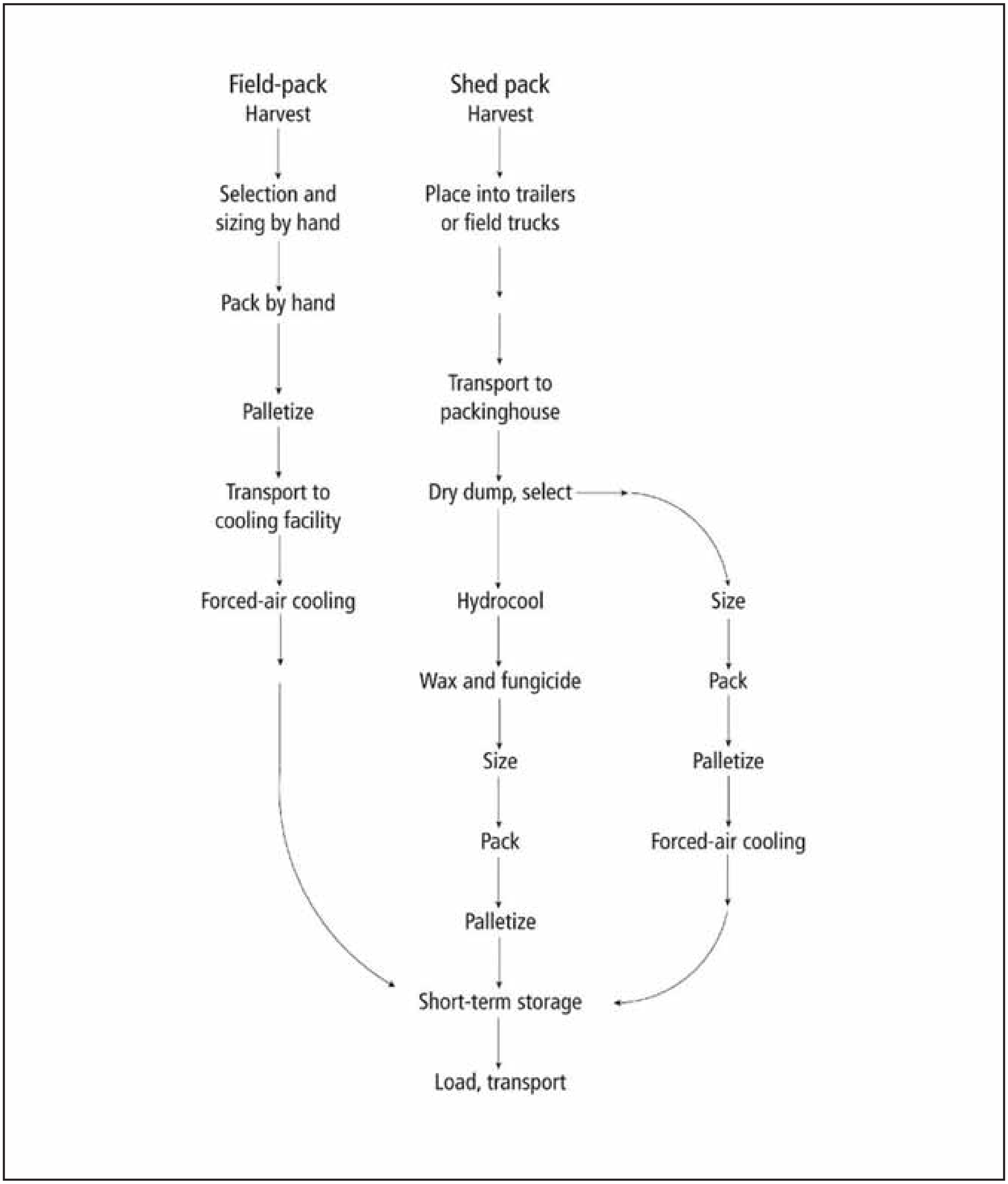
Figure 8 Post-harvest Handling of Immature Fruits and Vegetables



Source: Kader, 2002.

7 Full details of the requirements for handling specific horticultural crops during each of the crucial stages in harvest and post-harvest operations lies beyond the scope of this guide. One online source for this information is the website of the University of California, Davis Postharvest Technology Research and Information Center (http://postharvest.ucdavis.edu).

Figure 9 Post-harvest Handling of Melons



Source: Kader, 2002 (DANR Pub 3311: Figure 33.11)

Field Harvesting and Packing

Gentle handling of horticultural products is essential for protecting their quality and extending their shelf life. Manual and animal-powered activities are often used, and in many cases manual harvesting remains the preferred method for delicate high-value products. Most horticultural commodities are harvested manually, including those grown in highly industrialized nations. Energy requirements during harvesting include mechanical energy for digging up root and tuber crops and to operate mobile field packing operations. Harvesting early in the morning when air temperatures are cooler helps reduce energy requirements and costs for cooling. Diesel and gasoline-powered equipment is also used for some harvesting activities. These are described in more detail in the following sections.

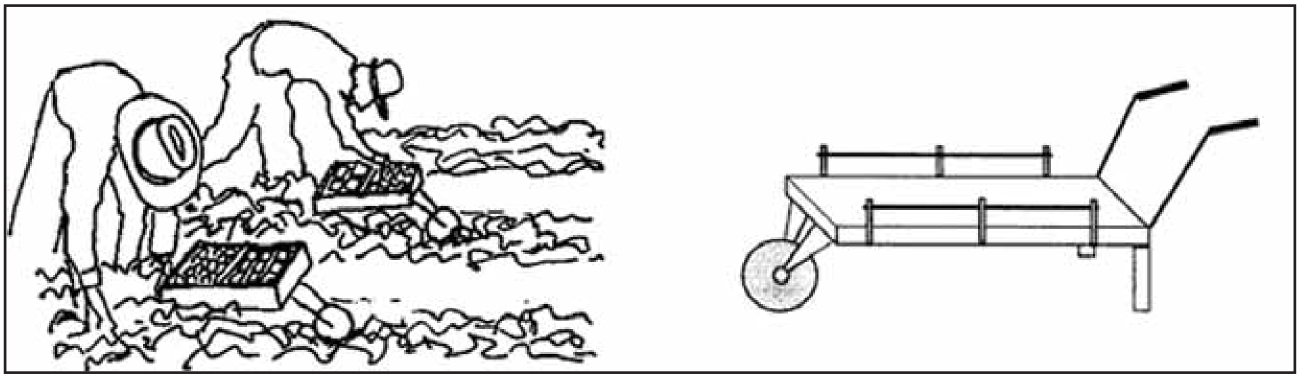
Manual/Low-tech Technologies

Manual harvesting: The methods used for harvesting most horticultural crops require only simple hand tools for cutting and collecting produce.

Animal powered: Oxen-powered activities include digging, turning the soil, and cutting away plant materials from roots and tuber crops).

Field packing: The need for a packinghouse can be eliminated by the use of simple hand-carts, and by sorting, grading, and packing during the harvest (see Figure 10). Reducing the number of times produce is handled between harvest and consumption will reduce mechanical damage and subsequent losses.

Figure 10 Field Packing



Source: Kitinoja and Kader, 2002; Kitinoja and Gorny, 1999

Fossil Fuel-powered Technologies

Mechanical harvesting: The fuel requirements for digging up root and tuber crops are similar to those for one-pass planting or weeding. The fuel consumption of a potato digger, for example, is 0.57 gallons of diesel fuel per ton of product (1.96 liters/MT).

Mobile field packing: The fuel requirements for tractor-drawn packing stations are similar to those for one-pass planting or weeding. For example, the expected energy use for mobile field packing for lettuce harvesting is 3.33 liters of diesel fuel per MT of product. Energy use depends mostly on the speed of harvesting. Thus, the average for lettuce is a good estimate for most crops, as lettuce needs to be harvested, trimmed, wrapped, and packed.

Transport of produce: Transporting produce from the field to the packinghouse requires animal carts or gasoline and diesel-powered vehicles. Vehicles are often over-loaded in the attempt to save on fuel, but any fuel savings are often offset by higher post-harvest losses and quality problems caused when produce is crushed in transit. Low-quality packages stacked too high and road vibration tend to damage produce significantly. (See Chapter 5: Transport of Horticulture Products for a detailed discussion on transport options and their energy requirements.)

Packinghouse Operations

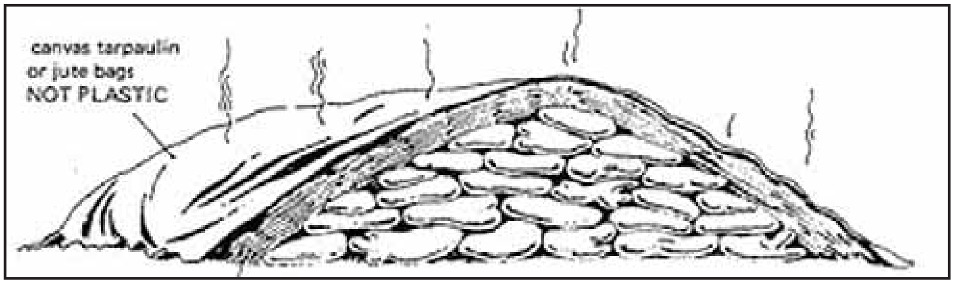
Packinghouses are often simple structures that provide shade and comfortable working environments for workers conducting manual post-harvest operations. More sophisticated packinghouses replace human labor with automated machinery and complex equipment to increase output per unit time. Manual handling is recommended for many commodities, and is the best choice for delicate produce. In countries where labor costs are high, equipment powered by electricity or fossil fuels often is used in place of manual practices.

Since there are more than 250 commercial horticultural crops grown in the world, and each packinghouse operation is a combination of many choices regarding handling technologies, there are no simple "rules of thumb" for energy requirements per metric ton of product. However, this section describes a sample of representative post-harvest technologies, criteria for selecting them, and examples of their capital and operating costs.

Manual/Low-tech Technologies

Field curing: Field curing refers to leaving harvested commodities in windrows or piles in the field (covered to protect them from direct sun) to allow bulb crops to dry before handing or storage, and for root and tuber crops to undergo natural healing of harvest wounds (see Figure 11).

Figure 11 Field Curing



Source: Wilson, J.

Curing: Curing of onions, garlic, and flowering bulbs generally takes place directly following harvest to allow the external layers of skin and neck tissue to dry out prior to handling and storage. If local weather conditions permit, these crops can be undercut in the field, windrowed, and left to dry for five to ten days. The dried tops of the plants can be arranged to cover and shade the bulbs during the curing process, protecting the produce from excess heat and sun damage. The dried layers of "skin" then protect the produce from further water loss during storage.

Cleaning/washing: Spray washing, brushing, or wiping of produce in the packinghouse is often done by hand. If water is used, the energy cost for pumping and for cleaning the water will depend on how much produce moves through the facility, and how much water is needed to clean the produce. Cleaning root vegetables requires much more water than the amounts used to wash other types of crops (see Case Study #2).

Disease and pest management: Fungicide sprays for fresh produce can be accomplished using simple hand pumps, using perforated trays and drainage basins.

Sorting and grading: Sizing rings and color charts can be used to visually sort and manually grade fresh produce. Simple tools such as rulers or calipers can be used to measure size or length.

Packing: Hand packing in plastic crates, fiberboard cartons, or locally made containers lined with plastic bags can be done by count or by weight. Hand packing typically is used for all delicate produce, as well as for any place-packed or count-packed commodities.

Natural air ventilation: Thermal chimneys can be added to existing structures or included in the design of new facilities to provide natural cooling of the packinghouse environment. As shown in Figure 12, air flow is greatly enhanced by the natural flow of air from cooler zones at the base of the structure and up through the warmed section and out. This type of ventilation is useful for cooling working spaces, but should not be used for storage rooms. Solar-powered fans can be used if passive ventilation is inadequate and other sources of electricity are not available. (See section on Renewable Energy-Powered Technolo-gies for a description of the operation of these fans.)

Case Study 2: Post-harvest / Packinghouse Operations in Lebanon

Context: Citrus growers and marketers in South Lebanon, through the 2004-2006 (USAID CEDARS Project) http://www.chflebanon.com/cedars/Pages/mission.html

Problem statement: How to reduce losses of Valencia oranges during storage and increase revenues for growers and marketers in Lebanon?

Background: Citrus crops in southern Lebanon were being left on the trees as a stop-gap storage method because of the lack of facilities for cleaning, sorting, waxing and cold storage. Oranges left on the trees had to be sprayed with pesticides on a weekly basis to prevent insect damages and suffered from high levels of water loss and texture degradation. The resulting produce was of low market value even though there was high consumer demand due to the low volume of oranges available in local markets a few months after the end of the regular harvesting period.

Technology selected to address the problem: A small packinghouse was constructed by the CEDARS Project and growers were encouraged by the staff to utilize the facilities for cleaning, waxing, packing, cooling and temporary cold storage of their oranges at 8 °C. The produce could be harvested at its proper maturity and kept at its peak quality for much longer than was possible under ambient conditions. Energy use for packinghouse operations and cold storage is estimated at 2 kWh per MT and 35 kWh per MT per day respectively at a subsidized price of US$0.12 per kWh in 2006 (electricity rates in 2008 were much higher at $0.20 per kWh).

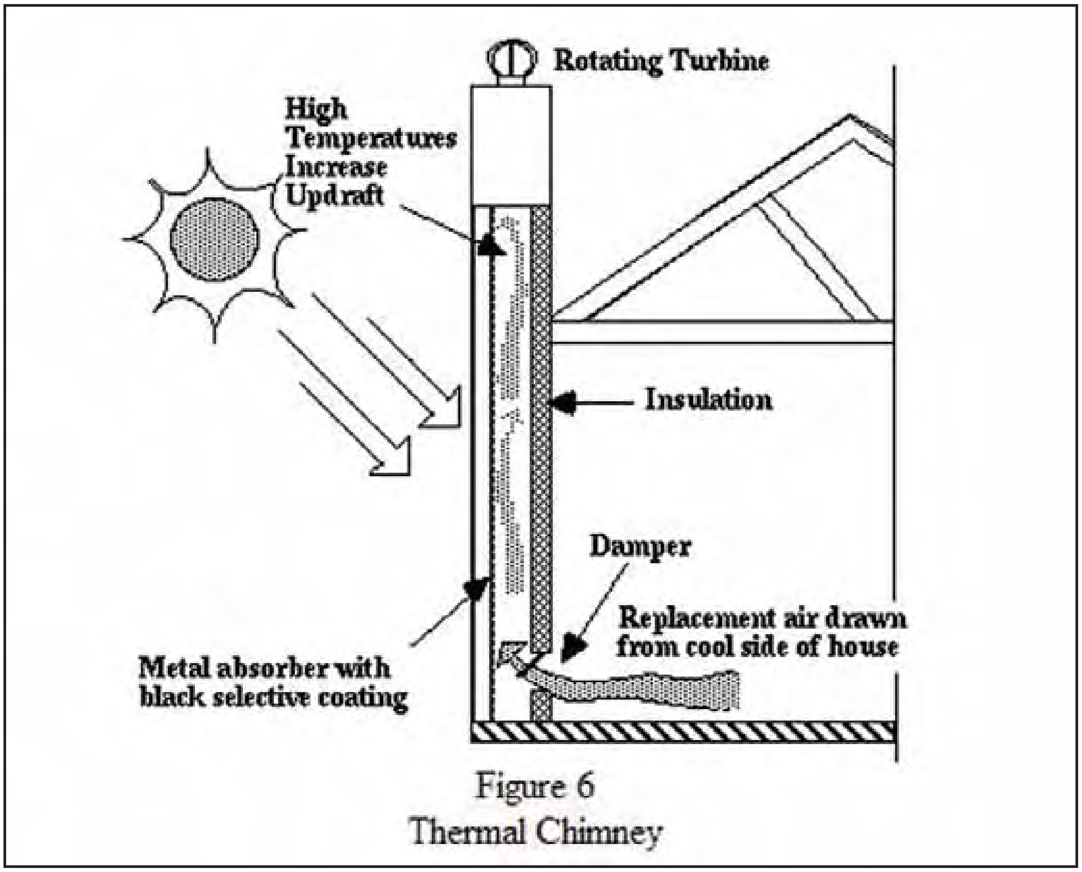
Results: Pesticide sprays in the orchard were no longer needed, postharvest losses were reduced and quality and market value improved. Cold storage fees paid by growers (to cover energy costs and a reasonable fee for product handling) were more than compensated for by reduced pesticide costs and increased revenues from sales of higher quality oranges a few weeks to a month after the peak harvest season ended.

Citrus crops are soaked and washed after arriving at the packinghouse. After waxing and drying in a heated air tunnel, the oranges undergo a machine sorting step (shown below) and are separated into four sizes. The fruits are then hand packed into 5kg packages (shown at left) and sent to the cold storage rooms or to the market.

Photo Credits: Hala Chahine 2004

Evaporative cooling of a packinghouse: Passive evaporative cooling of the work environment can be achieved by wetting the walls of a packinghouse or by using porous materials on one end of the structure (such as straw pads wet with water, as commonly found in large greenhouses). This simple method can provide active cooling of the working areas via water evaporation when air is pulled through the wet pad or wall by low-speed ventilation fans. This can be highly effective in dry climates but much less so in areas of high humidity.

Figure 12 Use of a Thermal Chimney for Low-Energy Cooling



Source: Sourcebook - Passive Solar Design http://www.greenbuilder.com/sourcebook/SourcebookContents.html

Fuel-powered and Electric Technologies

Curing with heated air: If forced hot air is used to cure onions, garlic, and other bulb crops, a curing time of one day or less at 35°C to 45°C and 60 to 75% relative humidity (RH) is recommended. Energy requirements will depend largely upon the ambient temperature during harvest, which will determine how much heat is required to achieve the necessary temperature for curing.

For example, for curing sweet potatoes, 4 to 7 days and 90% RH at a maximum temperature of 30°C are recommended. Humidifiers are commercially available, but simply wetting the floor will help maintain a high RH. A heater capacity of 4,440 BTU per hour (1.3 kWth) is required to heat 1 MT of sweet potatoes from 15°C to 30°C in 24 hours [31 kWh-th per metric ton]. A heater is not required to maintain the potatoes at 30°C. Once the crop is warmed it is allowed to return slowly to ambient temperature.

If the ambient temperature is significantly higher than 15°C during the harvest, energy use will be substantially decreased. However, if the ambient temperature is greater than 30°C, cooling must be used since curing will not occur at temperatures above 30°C.

Cleaning / washing: Mechanical washers use sprayers, roller brushes, air dryers, and conveyors to move produce through a packing line (see Figures 13 and 14 for different washing operations). Conveyors usually have motors of ½ to 2 hp (requiring 300 watts to 1.5 kW of electric power). Drying can be done using air knives and brushes with flipper bars, requiring unheated air and simple conveyor systems.

Figure 13 Banana-Packing House

Photo Credit: Introduction to Fruit Crops and Overview of the Text; http://www.uga.edu/fruit/chapter1.html

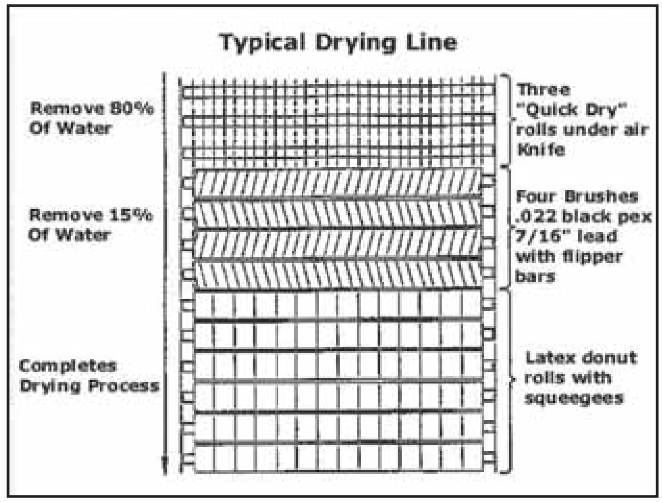
Figure 14 Washing Ginger

Photo Credit: Adel A. Kader

Figure 15 Drying Citrus Crops after Washing

Photo Credit: Hala Chahine

Figure 16 Typical Line Drying



Source: Industrial Brush Corporation; http://www.industrial-brush.com/ap_dry.html

Waxing and drying: Washer/dryer machines include water sprayers, air heaters (electric, natural gas or propane, adjustable temperatures) and blower motors (for air knives) with power requirements of 4 to 10 hp (3 to 7.5 kWe) (see Figures 15 and 16 for examples of drying operations). Electricity use for washing, waxing, and drying, based on lemon and orange packing, is 1 to 2 kWh/MT, while natural gas use is 60 to 90 MJ/MT. In many countries, it may be legal to use solvent-based wax formulations that often do not require heated air to dry the wax.

Disease and pest management: Hot water treatment dips can be heated using wood or coal fires, propane, natural gas, or electric or solar water heaters (see Table 6 for an estimate of the energy needed to heat water by each of these sources). Hot water treatment to recommended temperatures (typically 40°C to 52°C for 2 to 5 minutes) must be followed by ice baths to quickly reduce temperature.

Temperature requirements vary by the commodity being treated, but typically range from 40°C to 52°C, requiring 9.2 to 14.7 kWh of energy to raise 400 L of water from ambient temperatures of 20°C to 25°C via resistance heating. Hot water dips can be heated using propane or electricity for more even control of temperature.

Table 6 Electricity and Fuel Requirements for Water Heating

Ambient Water Temp (°C)	Target Water Temp (°C)	Water Flow (liters/hour)	Electricity use for Resistance Heating (kWh)	LPG Propane (liters)	Propane or Natural Gas (MJ)
20	40	400	9.2	1.5	38.0
20	52	400	14.7	2.5	63.3
25	40	400	6.9	1.2	30.4
25	52	400	12.4	2.1	53.1
30	40	400	4.6	0.8	20.2
30	52	400	10.1	1.7	43.0
20	40	1,000	23.0	3.8	96.1
20	52	1,000	36.7	6.1	154.3
25	40	1,000	17.3	2.9	73.4
25	52	1,000	30.9	5.1	129.0
30	40	1,000	11.5	1.9	48.1
30	52	1,000	25.2	4.2	106.3

Sources: LennTech Energy and Cost Calculator for Heating Water, 2008; http://www.lenntech.com/calculators/energy-cost-water.htm and http://www.apricus.com/html/solar_energy_calculator.htm

The figures in Table 6 assume that the heater efficiency for propane or natural gas heating is 85%, and that the energy density of LPG/propane = 25.3 MJ/liter = 7 kWh/liter.

Sorting / Grading: Mechanical sizing using conveyor systems can speed sorting and grading (see Figure 17). Diverging bar roller sizers, belt sizers, and other simple conveyor-type sizing machines are typically designed with 1 to 2 hp motors that require 0.75 to 1.5 kW of electricity. Electricity use for sorting/sizing ranges from 0.8 to 1.7 kWh/MT, based on data available for lemon and orange packing.

Packing: Machine packing using automated weighing and bagging is most useful for bulk packages of less delicate commodities such as carrots or potatoes. Electricity use for packing is 0.7 to 2.2 kWh/MT, based on lemon and orange packing costs.

Figure 17 Simple Sizing Table for Onions

Photo Credit: FAO; http://www.fao.org/docrep/008/y4893e/y4893e0x.jpg

Renewable Energy-powered Technologies

Solar water heating can reduce substantially the electricity or propane requirements, saving 80% to 90% of the fuel that would otherwise be required.

Solar collectors: Simple flat plate solar collectors with single glazing can be made locally and are commercially widely available in most of the world. A solar collector is the key component of an active solar-heating system. Solar collectors absorb solar energy, and the resulting heat is transferred to water or air. Flat-plate collectors are the most common type of solar collector for low-temperature water Solar water heating can reduce substantially the electricity or propane requirements, saving 80 to 90% of the fuel that would otherwise be required. Simple flat plate solar collectors with single glazing can be made locally and are commercially widely available in most of the world (see Figure 18).

A solar collector is the key component of an active solar-heating system. Solar collectors absorb solar energy, and the resulting heat is transferred to water or air. Flat-plate collectors are the most common type of solar collector for low-temperature water or air heating applications. A typical flat-plate solar collector is made up of an insulated box (wood, metal, plastic, etc.) with a transparent glass or plastic cover and a black absorber plate. These collectors are useful in producing hot water or air at temperatures as high as 80°C.

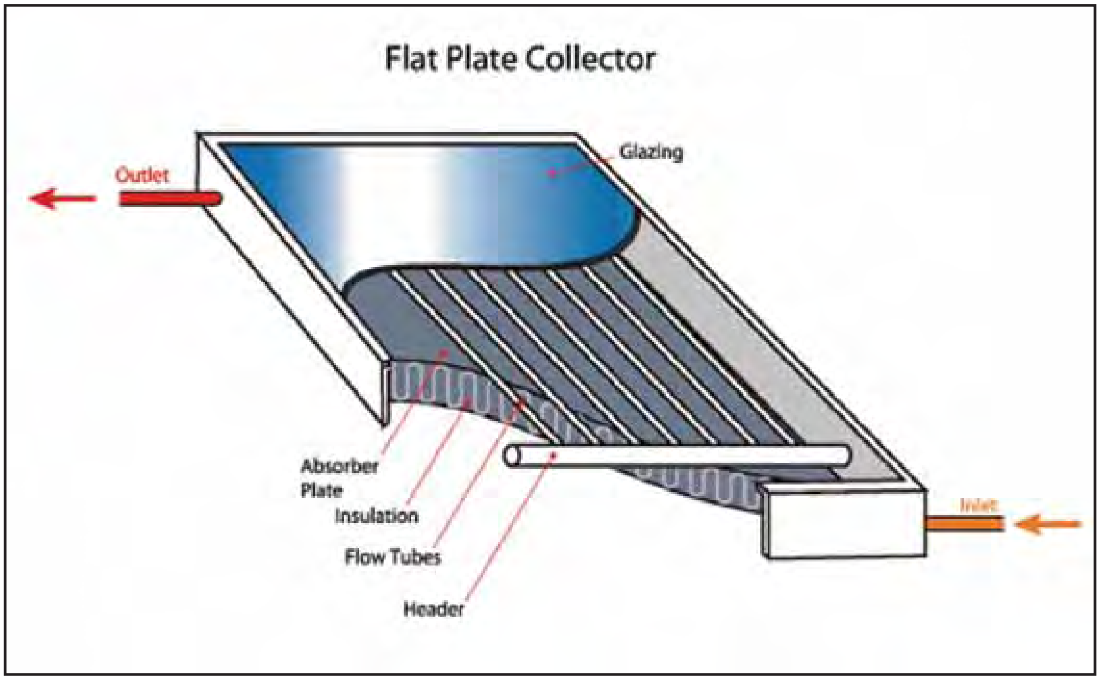
The amount of useful heat (in the form of hot water or hot air) that a solar collector can produce depends on the intensity of incident solar radiation, the percentage of sunlight reflected and absorbed by the transparent cover, the percentage of transmitted solar energy absorbed by the collecting surface, and the temperature difference between the incoming heat transfer fluid (air or water) and the desired outlet temperature.

Storing the water that will be used for hot water dips inside a large outdoor tank that is painted black and deliberately left exposed to the sun can increase the ambient temperature of the water to 30°C and reduce subsequent heating costs by 30% or more.

Integral Collector Storage for heating water: In an Integral Collector Storage (ICS) unit, the hot water storage tank is the solar absorber (see Figure 19). The tank or tanks are mounted in an insulated box with glazing on one side and are painted black.The sun shines through the glazing and hits the black tank, warming the water inside the tank. Some models feature a single large tank (100 to 200 L) while others feature a number of metal tubes plumbed in series (100 to 200 L total capacity).The single tanks are typically made of steel, while the tubes are typically made of copper.These collectors weigh 125 to 200 kg when full, so wherever they are mounted, the structure has to be strong enough to carry this significant weight. Single glazed collectors like this have adequate efficiency for low temperature applications, of less than about 50°C. Higher temperatures require double glazing and higher levels of insulation around the collector.

Solar-powered fans: Ventilation in the roof of a building will greatly reduce the buildup of heat during the day, and solar-powered fans[8] can provide enough air movement to use an evaporative cooler in small scale cool storage operations (see Figure 20). Solar-powered exhaust fans (including the 10 to 20 watts peak solar panel) retail for $400 - $600 and are available for both flat and pitched roofs. The exhaust rate ranges from 700 CFM to 1,400 CFM.

Figure 18 Flat Plate Solar Collector



Source: How Solar Thermal and Photovoltaics Work;
http://southface.org/solar/solar-roadmap/solar_how-to/solar-how_solar_works.htm

8 Solar Living Sourcebook (12th edition).

Figure 19 Solar-powered Ventilation

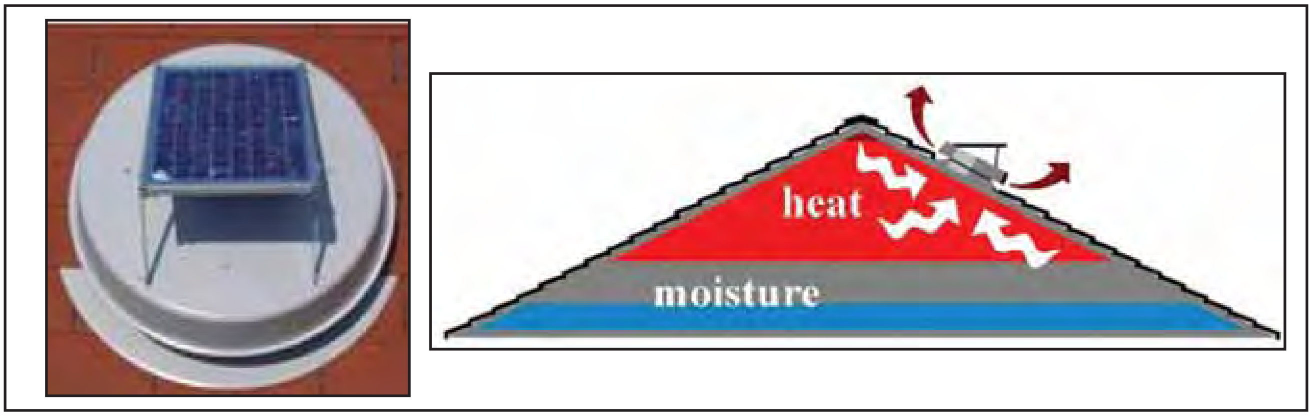


Photo Credit: Creative Energy Technologies Inc; http://www.cetsolar.com/12volt.htm

The following tables give some comparative details regarding the costs of various packing and packing-house operation technologies that require power sources.

Table 7 Capacity and Energy Use of Packinghouse Technologies

Packinghouse Technology	Typical Capacity	Energy Use (kWh, liters or BTU)
Submersible electric water pump (½ hp to ¾ hp)	2,400 to 3,600 L/hour	0.4 to 0.6 kW for 8 hours/day = 3.2 to 4.8 kWh/day
Mechanical washing (water pump for sprayers)	200 L/hr	
Air knives dryer (blower fan)	varies	300 watts to 1.5 kW for 8 hours/day
Waxing and drying (heater and blower fan)	varies	1 to 2 kWh or 60 to 90 MJ /MT (= 1.5 to 2.3 L propane)
Mechanical sizing or grading con-veyors	varies	300 W to 1.5 kW for 8 hours/day
Heater for curing	1 MT	96,000 BTU (4000 BTU/h to raise temp from 15°C to 30°C in 24 hrs) or 3.6 L propane
Hot water dip treatment (water heater)	800 L/hour	18 to 30 kW to raise temp from 20°C to 40°C
Cooling (ice bath) after hot water treatment	5 to 12.5 kg ice per kWh	27 to 67 kWh /MT

*Varies widely, cost/MT is based upon daily throughput. If capacity is not maximized, energy use cost per MT can increase considerably.

Source: Information compiled by Lisa Kitinoja

Along with their approximate costs, some alternative postharvest technologies are presented below in Table 8.

Table 8 Estimated Costs of Alternative Post-harvest Technologies

Post-harvest Technology Budget	Technologies Available		
	Packinghouse	**Cooling / Cold Storage**	**Transport**
Under $100	Manual handling and packing	Shade cloth	
$200-$600	Field packing carts	Evaporative cooling, night air ventilation, ice	Evaporative cooling trailer or insulated box
$600-$2,000	Solar water heater	Zero-energy cool chamber	Porta-cooler trailer
$2,000-$5,000	Traditional packing house equipment line (one)	Solar chiller	Insulated boxes cooled with 3 ton A/C unit
$5,000- $10,000		Retrofit 20 reefer for cold room storage, owner built small-scale cold room	
$10,000 - $20,000	Shed type packinghouse	Hydro-cooler	
Over $20,000	Fully equipped small-scale packinghouse	Pre-fabricated small-scale cold storage room	
		Vacuum cooler, intermedi-ate scale cold rooms	Refrigerated (reefer) transport

Source: Information compiled by Lisa Kitinoja

Chapter 3: Cooling and Cold Storage

Cooling

Cooling is one of the most important steps in the post-harvest handling chain. Reducing the temperature of produce after harvesting can greatly reduce respiration rate, extend shelf life, and protect quality, while reducing volume losses by decreasing the rates of water loss and decay. This first cooling step is usually referred to as "pre-cooling" since it is done as soon as possible after harvest and before produce is placed into cold storage or loaded into refrigerated trucks or marine containers.

Post-harvest shelf life depends on keeping fresh produce cool. As product temperatures increase, the rate of deterioration increases significantly. For example, as indicated in Table 9, with a temperature increase of 10°C the rate of deterioration will double or even triple, resulting in much shorter post-harvest life.

Importance of Cooling and Cold Storage

The initial cooling, processing, and cold storage of fresh fruit and vegetables is among the most energy intensive segments of the food industry. Significant levels of refrigeration and heating are needed to slow down spoilage and maintain pre-harvest freshness and flavor of ripe fruit and vegetables. Cooling the fresh fruit and vegetables before processing removes the "field" heat from the freshly harvested products in time to inhibit decay and help maintain moisture content, sugars, vitamins, and starches. Blanching of fresh vegetables such as asparagus, broccoli, and cauliflower helps maintain product texture and color. The quick freezing of processed fresh fruit and vegetables helps maintain the quality, nutritional value, and physical properties for extended periods. The refrigeration systems, especially for the fruit processors, usually operate at their heaviest load during the summer day-time hours when electrical costs and outdoor temperatures are the highest.

--Hacket, Chow, and Ganji (2005)

Table 9 Effect of Temperature on the Rate of Deterioration of Fresh Produce

Temperature (°C)	Relative Rate of Deterioration	Relative Shelf Life	Example of Potential Shelf Life in Days
0	1.0	100	45
10	3.0	33	15
20	7.5	13	5
30	15.0	7	2.5
40	22.5	4	1.3

Source: Adapted from data in USDA Handbook 66

Table 10, calculated from known respiration rates of selected produce at varying temperatures (USDA Handbook 66), provides some examples of how lowering temperatures by even a small amount during the marketing period, from ambient temperature (30°C to 35°C) to 15°C, will extend post-harvest life at least four times longer than leaving produce at 35°C. Case Study #3 compares the costs and benefits of using a cold chain approach to harvesting and transporting mangoes in India. Even with high fuel costs, there will likely be greater profits because of the lower post-harvest losses and higher product quality.

Table 10 Post-harvest Life Increases with Decreased Product Temperature

Commodity	Recommended Temperature for Handling and Storage (max post-harvest life)	Post-harvest Life at 35°C* (ambient temperature)	Post-harvest Life at 25°C	Post-harvest Life at 15°C	Increased Marketing Time Available at 15°C
Cabbage	0°C (6 months)	2 weeks	4 weeks	8 weeks	4X
Carrots	0°C (6 months)	2 weeks	4 weeks	8 weeks	4X
Tomatoes	15°C (14 days)	3 days	6 days	14 days	5X
Peppers	12°C (20 days)	3 days	7 days	15 days	5X
Potatoes	5° to 7°C (5 to 10 months)	2 weeks	4 weeks	8 to 10 weeks	4X
Spinach	0°C (14 days)	1 day	2 days	5 days	5X
Sweet potatoes	15°C (4 to 6 months)	1 month	2 months	4 to 6 months	4X

Source: Kitinoja, calculated from data provided by USDA Handbook 66
* Typical post-harvest losses include weight loss, decay, yellowing of green vegetables, wilting or shriveling (water loss), development of bitterness (carrots, cabbages), textural changes (toughening, pithiness), over-maturity or over-ripening (tomatoes).

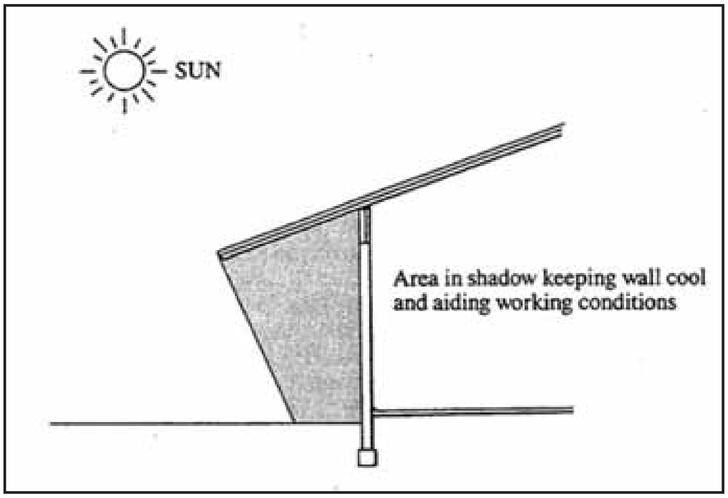
Manual/Low-tech Technologies

Shade: Covering fresh produce and protecting it from direct sunlight is a low-cost way to reduce heat gain. Using roofing or cloth tenting for providing deep shade over all assembly points and working areas is recommended. A deep overhanging roof extension (at least one meter) can provide shade for windows or doorways and a light colored or reflective roof can reduce surface temperatures and temperatures under the shelter by up to 20°C (see Figure 21).

Cold water (from deep wells or mountain streams): Well water is often much cooler than air temperature in most regions of the world. Water from deep wells and mountain streams typically will be measured to be at a temperature that is the average annual air temperature for the area. Well water can be used for hydro-cooling and as a spray or mist to maintain high relative humidity in the storage environment. Water from streams, however, is often contaminated and is not suitable for contact with food items.

Passive evaporative cooling: As described in Chapter 2, wetting the walls of a packinghouse or using porous materials on one end (such as found in large greenhouses) can provide passive cooling via water evaporation from the wall when air is pulled through the wet pad by ventilation fans.

Figure 20 Shading to Reduce Wall Heating



Source: Walker, D.J. 1992.

Case Study 3: Integrated Cold Chain: Mangoes in India

Context: The data collected by in Punjab, India in 1997 for the USAID ACE-India Project and updated in 2008 for the USTDA-sponsored **India Cold Chain Workshop Series** (Kitinoja 2008, unpublished) http://coldchainbiz.com/.

Problem statement: How do the estimated costs and expected benefits compare, for cooling horticultural produce and maintaining the cold chain during handling, storage, transport and marketing of high-value mangoes?

Costs: Cool storage facility fees; power for pre-cooling, storage and cool transport; labor for refrigerated cargo handling.

Benefits: Lower postharvest losses; longer shelf life and marketing period; higher quality; higher market price

Two metric tons of mangoes are harvested at the peak of the season (June 15 to 20) in India, and are handled either at ambient temperatures (30°C to 35°C) or via an integrated cold chain (15°C), where refrigeration and cool transport costs are relatively high: $1,000 (or $0.50 /kg). All other packing and marketing costs are the same for the two cases.

	Ambient temperature	Cold chain
Post-harvest losses	35%	10%
Quality classes:	20% highest	60% highest
	60% second	30% second
	20% lowest	10% lowest
Total volume sold	1,300 lbs	1,800 lbs
Marketing period	June 15 – June 28	June 25 – July 31
Average price/kg	$1.00	$2.00
Expected sales	$1,300	$3,600
Cost of cooling, cold storage,		
and reefer transport	0	$1,000
Sales minus cost of cooling	$1,300	$2,600
Added profit		+ $1,300 per 2 MT load

Notes:

Even though the cost of using the cold chain is high, the ability to extend the marketing period beyond the peak of the season and the resulting higher prices mean that the additional profit potential from refrigeration is significant (an added $0.65 per kg), when compared to using no cooling.

Fossil Fuel-powered and Electric Technologies

Room cooling: Room cooling is a simple but slow method of reducing the temperature of produce prior to cold storage, where packages of produce are placed inside a cold room and allowed to slowly cool down. Room cooling commonly requires 24 to 48 hours or more, and is not recommended for highly perishable crops. Fans should be capable of providing 90 CFM/MT during initial cooling. The fan speed can be reduced to provide air flow at 18 to 25 CFM/MT once target temperatures have been achieved.

Ice: A central ice-making plant and ice distribution system allows produce cooling in locations where electricity and mechanical refrigeration are not available. This was the original basis for the development of the long-distance perishables business in the United States. However, cooling using ice is relatively inefficient because only about half the cooling effect is actually used to cool the produce. The rest is lost to heat exchange with the warm environment (Thompson and Chen 1989). In addition, there can be significant loss of ice as it melts in transit from the central refrigeration plant to the cooling facility. Unless the packages and ice can be used within a well-insulated environment (such as in an ice chest-style container), at least 50% of the original ice will be lost before it can be used.

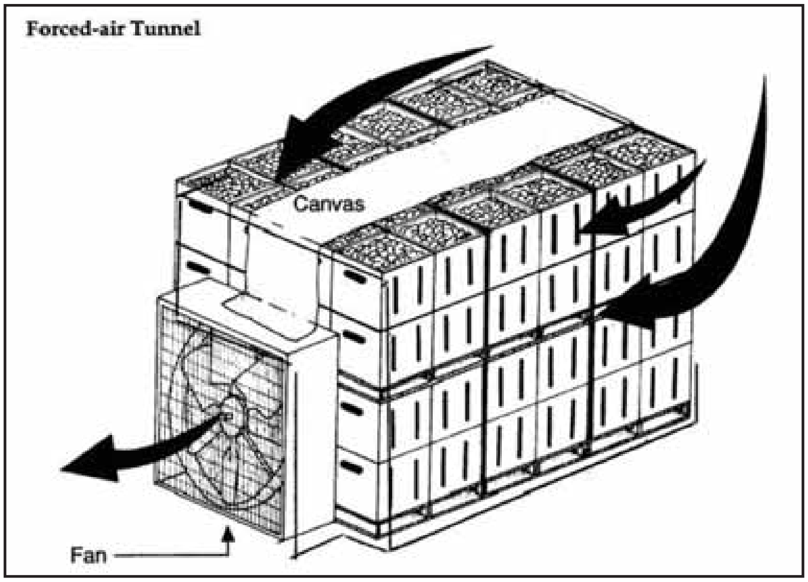
Melting one kg of ice has a cooling effect of approximately 316 BTU. One kg of ice will lower the temperature of fresh produce or water weighing 3 kg by about 28°C.

As an ice machine has several electricity-driven components, making ice is an energy-intensive process and can be expensive. Most ice machines produce between 5 and 12.5 kg of pure ice per kWh. One of the most energy efficient ice makers available, Crytec's Bubble Slurry™ Ice machine Model CR-004 produces 18.5 kg of pure ice per kWh and has a capacity of 146 kg of pure ice per hour. Since 330 kg of ice would be required to cool one MT of fresh produce by 28°C, requiring up to 66 kWh, the cost of making ice for this purpose can often be prohibitive.

Evaporative forced air cooling: Using an electric fan and a wet pad to move cool air through containers of fresh produce will speed the cooling process. Produce temperatures can be reduced using evaporative cooling to a few degrees above the ambient dew point temperature (the temperature at which moisture begins to form on a slick surface, indicating 100% saturation of the air with moisture). The fan must be able to provide airflow of 1 L/sec/kg against a wide range of static pressures. Doubling the airflow will speed cooling somewhat but the cost will rise considerably because the fan would need to have approximately four times greater horsepower to accomplish the same work.

Forced air pre-cooling inside a cold room: Forced air (FA) cooling can speed the cooling of a batch of packaged produce stacked inside a cold room from two or more days to less than 8 hours. If a cold room with adequate refrigeration capacity is available, adding a portable forced air cooling tunnel that can cool 4 pallets at a time will increase the fan's power use by only 800 to 1,500 watts per hour. A cold room with 5 tons of refrigeration can cool 3 MT of horticultural produce from an initial temperature of 27°C to a target temperature of 2°C in 6 to 8 hours (see Figure 22 and Case Study #4).

Figure 21 Small-scale Model of a Portable Forced Air Cooling Tunnel



Source: Gast, Karen L.B. and Rolando Flores, 1991

Case Study 4: Pre-Cooling Operations in Indonesia

Context: Bali, Indonesia, Bedugul strawberry growers and marketers involved in the 2008 USAID AMARTA Project, implemented by DAI. http://www.amarta.net/

Problem statement: How to reduce losses of strawberries during shipping and increase revenues for growers and marketers in Indonesia?

Background: Strawberry growers in Bali were losing 30% of the volume and market value of their strawberries before the berries could be sold to supermarket chains in the capital city Denpasar. Strawberries were being picked under-ripe as an attempt to increase shelf life at ambient temperatures, but the quality was low since berries were not very sweet or fully red, and water losses were very high. Thus, farm gate prices offered by supermarket buyers were low. Ambient temperatures of 30°C to 35°C in the local packing shed were contributing to water loss rates of 10% per day when berries were sorted, graded, and hand packed.

Technology selected to address the problem: With the assistance of AMARTA Project staff, growers learned to select berries at near full ripeness, and then grade and field pack the fruits. They approached managers of Big Tree Farms in Bedugul and requested assistance with pre-cooling. Using a locally constructed portable forced air pre-cooling unit inside an existing under-utilized walk-in cold room at Big Tree Farm's packinghouse, 0.8 MT strawberries can be cooled in less than two hours. Energy use to pre-cool the berries from 35°C to 2°C is estimated at 40 to 50 kWh per MT at an electricity price of approximately Rp 520 per kWh (equivalent to US$0.05 per kWh; business rates vary by monthly usage and are provided a heavy government subsidy).

Results: Big Tree Farms set a per kg fee for pre-cooling strawberries that covered their energy costs and provided a reasonable profit, and the growers who paid the fees made more profits because they received a higher farm gate price for their better quality, pre-cooled, fully ripe berries. Post-harvest losses were reduced to less than 5% and supermarket buyers were pleased since the better quality, sweetness and longer shelf life also allows the supermarket to improve their profits by reducing losses and selling more berries to consumers at a higher retail price.

Locally constructed portable forced air cooling unit (cost US$150) used to pre-cool strawberries packed in plastic consumer packages stacked in large plastic crates. Crates hold 10kg and can be stacked up to 5 high, 2 deep and 8 long along each side of the cooling tunnel for a maximum volume of 800kg per load.

Photo Credits: Lisa Kitinoja, 2008

The area of the vents on the sides of produce containers should be at least 5% of the container surface area in order to accommodate airflow without excessive pressure drop across the box. Fans for FA coolers usually operate within a typical range of 0.5 to 2.0 L/kg/sec (1 L/kg/sec equals about 1 CFM per lb). Doubling the airflow rate will speed cooling somewhat (perhaps by 40%) but the energy cost will rise considerably because the fan would need to use 5 or 6 times as much power. For example, airflow for 3MT at 1 L/kg/sec and 1.3 cm w.c. (water column pressure) requires 1.12 HP (0.85 kW). If airflow is doubled, the fan size will need to increase to about 7 HP. Centrifugal fans with forwarded blades are suited for most small-scale cooling applications. Commonly available industrial propeller fans are more suited for applications with low air pressures. In the US prices typically range from $1,000 for a ½ HP fan to $1,600 for a 1 HP fan.

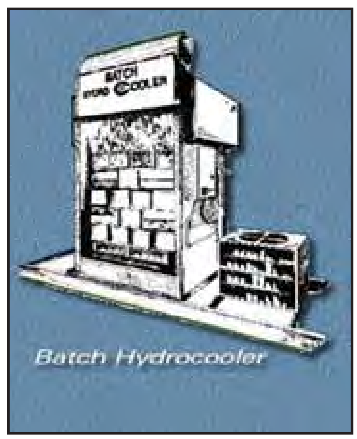
In an electricity use survey of produce coolers currently being conducted for the California Energy Commission, the early findings indicate that typical commercial forced air cooling has a seasonal average energy use of 55 kWh/MT, with a range of 22-27 kWh/MT. This includes some short-term storage prior to shipment. Efficient operations can operate at about half this average amount of electricity per MT. Product throughput affects energy efficiency, measured as kWh consumed per box, more than any other factor in an operation (Thompson and Singh, in press). Figure 23 shows an empty cold wall forced air station, and on the right a loaded forced air station with the tarp being pulled into place over the tunnel of pallets.

Figure 22 Forced Air Cooling

Photo credits: Adel A. Kader

Hydro-cooler: Water used for cooling must be kept very cold using ice or mechanical refrigeration. Water is a far better heat-transfer medium than air, so hydro-coolers cool produce much more quickly than forced-air coolers. In well-designed shower type hydro-coolers, small diameter produce such as cherries will cool in less than 10 minutes. Large diameter products such as melons will cool in 45 to 60 minutes.

Figure 23 Batch Hydro-cooler



Source: Norlock Refrigeration & Controls; www.norlockrefrigeration.com

Batch-style hydro-coolers will hold one or more pallets of produce and shower cold water over the tops of the stacked containers, allowing the water to filter down through the containers and contact the produce, removing heat as it passes down through the load. In the illustration (see Figure 24) the door is shown in its open position, but typically during operation the door would be closed to reduce heat infiltration and water losses.

Immersion hydro-coolers are large, shallow, rectangular tanks that hold moving chilled water. Crates or boxes of warm produce are loaded into one end of the tank and moved by hand or on a submerged conveyor to the other end where they are removed. Crushed ice or a mechanical refrigeration system keeps the water cold, and a pump keeps the water in motion. Most produce is only slightly buoyant so the individual produce items tend to stay submerged. The length of time the produce remains in the water varies with the initial conditions and desired ending temperature. Immersion-type hydro-coolers have longer cooling times than shower coolers because the water moves past the produce at a slower speed, but cooling speed can be improved if the water is properly agitated.

Table 11 compares the effects and costs of the principal different fossil fuel-powered and electric cooling technologies described immediately above.

Table 11 Comparison of Typical Product Effects and Costs

Effects and Costs	Forced Air	Hydro	Room	Ice
Typical cooling time (hours)	1 - 10	0.1 - 1	20 - 100	0.1 – 0.3
Product moisture loss (%)	0.1 - 2	0 – 0.5	0.1 - 2	no data
Water contact with product	no	yes	no	yes, unless bagged
Potential for decay contamination	low	high	low	low
Capital cost	low	low	low	high
Energy efficiency	low	high	low	low
Water-resistant packaging needed	no	yes	no	yes
Portable	sometimes	rarely	no	common
Feasibility of in-line cooling	rarely	yes	no	rarely done

Source: Thompson, et al., 1998

The following table provides information on the costs of various cooling methods and cooling operation technologies. The costs of forced air cooling and room cooling are approximately the same per MT, since forced air cooling uses more power but requires less time, while room cooling uses less power but takes a long time. Energy costs per MT increase whenever cooling equipment or facilities are not utilized to their full capacity. Cost estimates for energy use are not provided below due to the substantial volatility of energy prices (e.g., diesel, propane, kerosene, and electricity) and their geographic variability.

Table 12 Cooling Technology Characteristics

Cooling Technology	Purchase Price	Estimated Life of Operation	Typical Use, Size, or Capacity	Energy Use (kWh, liters or BTU) per MT
Evaporative forced air Cooling to 13°C (0.1 hp fan)	$400	6 years	0.5 MT	0.7 kWh
Evaporative forced air Cooling to 13°C (0.5 hp fan)	$1,300	6 years	1 to 2 MT	0.7 kWh
Ice put into packages (330 kg required to cool 1 MT by 28°C)	$6,000 to $10,000		5 to 12.5 kg ice per kWh	27 to 67 kWh (actual = 54 to 134 kWh since ½ of the ice is lost before cooling)
Hydro-cooling—shower type to 0° to 2°C	varies		3MT cooled in less than 1 hour	80 to 110 kWh
Hydro-cooling—immersion type to 0° to 2°C	varies		3MT cooled in 1 hour	110 to 150 kWh
Hydro-cooling—shower type to 7°C	varies		3MT cooled in 1/2 hour	35 to 100 kWh
Portable forced air cooling (1 hp) fan in existing cold room to 2°C	$1,600	6 years	3 MT cooled in 4 to 6 hours	55 kWh
Portable forced air cooling (1 hp) fan in existing cool room to 13°C	$600	6 years	3 MT cooled in 2 to 4 hours	35 kWh
Room cooling to 0° to 2°C	varies		varies	55 kWh
Room cooling to 13°C	varies		varies	35 kWh

Source: Information compiled by Lisa Kitinoja

Cool and Cold Storage

Cold storage in tropical and subtropical climates can have a high energy demand, but the costs of cold storage are often more than offset by cost savings from reduced product losses and better quality. Adequate insulation of the roof and walls of cold storage facilities can greatly reduce the power needed to maintain desired storage temperatures. Proper selection and sizing of the refrigeration capacity, coils, compressors, fans, and other equipment for their intended use will help improve energy efficiency in a cold storage building. Proper stacking of produce within the room and avoiding the overloading of cold storage rooms will also contribute to energy efficiency.

Different horticultural crops can have very different temperature requirements for optimizing storage life, largely depending upon their biological origins. Fruits and vegetables from the temperate zone have lower temperature needs (0°C to 2°C) than do crops from the tropics or subtropics (which can tolerate the lowest safe temperature of 12°C). For tropical and subtropical produce such as tomatoes, sweet potatoes, and papayas, cool rooms that can maintain a temperature of 12°C to 15°C are sufficient for enhancing post-harvest life.

A summary table of compatible groups of products for cold storage can be found in USDA Handbook 66 (available online in draft form at http://www.ba.ars.usda.gov/hb66/contents.html).

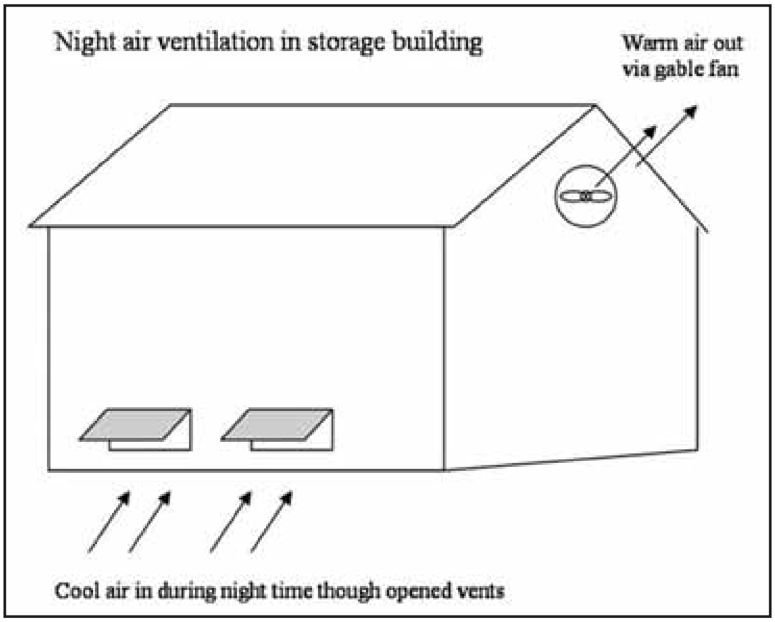
Manual/Low-tech Technologies

Painting storage buildings white or silver: This will reflect sunlight, reducing surface temperature and thus reducing the heat transmitted to the cold room through exterior walls.

"Outsulation" combined with thick high thermal capacity walls: Highly reflective insulating materials on the outside of the building will permit the inside walls to remain cool, especially if they are fairly massive with a high thermal capacity. Cooling the inside of the building and the inside walls at night significantly reduces the amount of energy required for refrigeration, and the thick walls (e.g., concrete block) act as a thermal "flywheel," with the external highly reflective insulation significantly limiting solar heating of the walls.

Radiant cooling: Radiant cooling can be used in dry climates with clear night skies to lower the air temperature in a storage structure if a solar collector is connected to the ventilation system of the building. By using the solar collector at night, heat will be lost to the environment through radiation to the cold night sky. Temperatures inside the structure of 4°C (about 8°F) less than night temperature can be achieved.

Figure 24 Night Air Ventilation



Source: Kitinoja and Gorny (1999)

Storage underground or in caves: The average temperature will be similar to average surface water temperatures in local rivers or streams, or the average annual air temperature in the region.

High altitude storage: Typically air temperatures decrease by 10°C (18°F) for every one kilometer increase in altitude. If handlers have an option to pack and/or store commodities at higher altitude, costs could be reduced. Cooling and storage facilities operated at high altitudes require less energy than those at sea level to achieve the same results. As a rule, night ventilation effectively maintains product temperature when the outside air temperature is below the desired product temperature for 5 to 7 hours per night.

Night air ventilation: If the outside air is cooler than the product being stored, natural convection, using manually operated vents, will work well and require no power (see Figure 25). If possible, the storage room should be opened only at night when air temperatures are lowest.

Simple cool storage facilities can be operated manually by opening the vents at night and closing them just before sunrise. A series of vents should be spaced around the perimeter of the building near ground level with a similar area of vents near the highest part of the storage building. This vent placement allows the warmer air in the top of the storage to exit the building via natural convection and draw in cool air from near ground level.

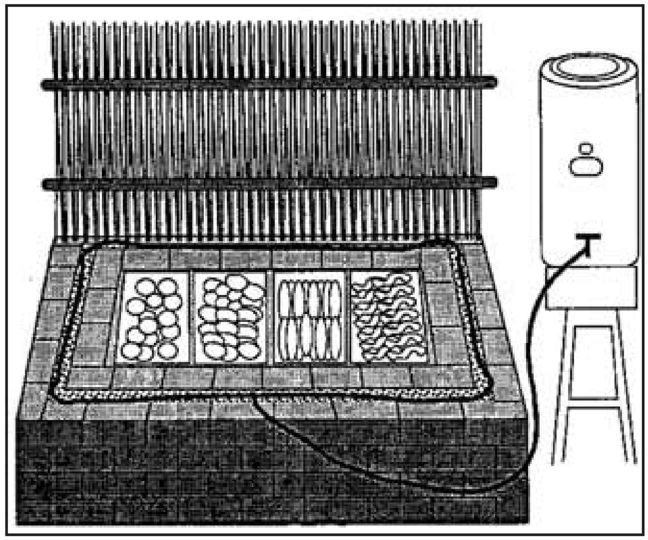
If natural convection is not sufficient, a small fan (60 to 100 watts) can be used to help move warm air out of the building via a roof vent. A fan placed near the peak or gable of a storage building should be operated only during the cooler hours of the night-time, allowing cool air to be pulled into the building to replace the warmer daytime air.

"Zero-energy" cool chamber: A specially designed, low-cost brick and sand unit kept moist can maintain an inside air temperature of 15°C to 18°C and a relative humidity of 95% when outside air temperatures are over 30°C. These chambers work best under dry conditions, such as during the dry season or in arid or semi-arid environments, and the small sized units (holding 100 to 200 kg of produce) require no electricity or fuel. Larger-sized cool chambers are constructed as a round walk-in room with a slatted floor and a small ventilation fan (60 to 100 W) added to the roof. Figures 26 and 27 show the construction of a cool chamber.

Figure 25 Corner of a Bricks and Sand Cool Chamber

Photo Credit: Lisa Kitinoja (1998)

Figure 26 "Zero Energy" Cool Chamber



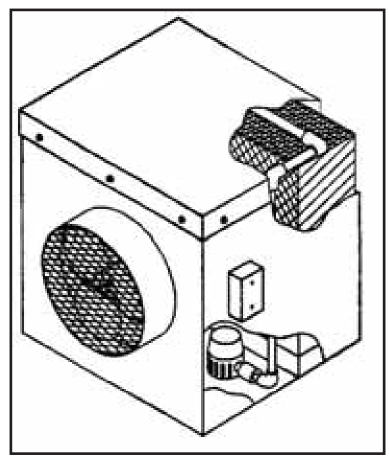
Source: Roy, S.K. (2007)

Fossil Fuel-powered Technologies

Evaporatively cooled storage rooms: Evaporative coolers, sometimes called "swamp coolers" or "desert coolers," use the evaporation of water to cool a storage room. Evaporative coolers have a low initial cost, and use much less electricity than conventional air conditioners. See Figure 28 for a drawing of an evaporative cooler.

In a direct evaporative cooler, a blower forces air through a permeable, water-soaked pad. The pads can be made of straw, wood shavings or other materials that absorb and hold moisture while resisting mildew. Aspen wood pads, also called excelsior, need to be replaced every season or two, and generally cost $20 to $40 for a set of two. As the air passes through the pad, it is filtered, cooled, and humidified. Evaporative coolers should be sized based on cubic feet per minute of airflow. Improperly sized evaporative coolers will waste water and energy and may cause excess humidity. Two-speed coolers are available that can handle varying cooling loads. A working model of an evaporative cooling unit with two moistened pads can be seen in action on the website http://www.consumerenergycenter.org/home/heating_cooling/evaporative.html.

Figure 27 Cut-away View of an Evaporative Cooler with One Pad



Source: Kansas Wind Power & Astronomy; www.kansaswindpower.net

Cooling to a few degrees above the dew point temperature is possible using evaporative cooling. Cooling is more energy efficient at lower fan speeds and more effective at lower percentage relative humidity levels (RH % is the percent of moisture in the air compared to the amount of moisture the air could contain).

Evaporatively cooled storage rooms require fans with a capacity of 0.3 m^3/second per MT of fresh produce (64 CFM/MT). Assuming the fan operates against a static pressure of 0.6 cm of water column and has 50% efficiency, the system will require 0.09 kWh per MT of product storage capacity for one day of operation. The fan will operate continuously when the outside air temperature is greater than the desired storage temperature. The fan should have the capacity to exchange the air in the room completely once every two minutes. The following table can help determine the size and energy use of evaporatively cooled storage rooms or small portable cooling units (see also Chapter 5: Transport of Horticultural Products).

Table 13 Estimated Equipment Sizing and Energy Use for Selected Evaporative Coolers

	40 m2 Cool Room (430 ft^2)	20 m2 Cool Room (215 ft^2)	Laege Porta-cooler (6 m^2 or 64 ft^2)	Small Porta-cooler (3 m^2 or 32 ft^2)
Capacity (MT)	10 to 13	5 to 6	0.8 to 1.0	0.4 to 0.5
Cubic meters	100	50	7.0	3.5
Cubic feet	3,500	1,765	256	128
Fan capacity (cfm)	1,664	768	128	64
kWh per day	0.9 to 1.2	0.45 to 0.54	0.07 to 0.09	0.04 to 0.05

Source: Information compiled by Lisa Kitinoja

Two-stage evaporative coolers have been developed that pre-cool air before it goes through the moistened pad. These new coolers are reported to be as effective as mechanical air conditioning, but their initial cost is high, about $5,000 for a 3-ton system, approximately the same cost as air conditioning units of similar size. However, the electricity required for evaporative cooling can be as little as 10% that required for an equivalent level of mechanical refrigeration cooling.

Mechanically refrigerated cold rooms: Cold rooms are a very common feature of horticultural operations, and come in many sizes and types. Capital costs and energy use estimates for small-scale cold rooms vary considerably. The new prefabricated cold rooms and used refrigerated highway vans (Figure 29) are the most expensive on an area basis (see Case Study #5). The least expensive options are used prefabricated cold rooms, if they are available locally, and owner-built facilities. Purchase costs for pre-fabricated cold rooms increase considerably for floor areas under the 40 m^2 used as a baseline floor area in Table 14. Large facilities with hundreds of square meters of floor area cost about the same as the new prefabricated rooms listed in Table 14.

Table 14 Cost of Purchase and Installation of Small-scale Cold Rooms

Types Small-scale Cold Rooms	Cost (USD per m^2)
New prefabricated	800
Used prefabricated	180 – 530
Highway van	590 – 800
Refrigerated marine container	620 – 760
Owner built	180 - 360

Notes: For facilities with about 40 m^2 floor area. Data for US installations.
Source: Based on Thompson and Spinoglio, 1996

Figure 28 Highway Van Used as a Cold Storage Room

Photo Credit: Lisa Kitinoja (2000)

Case Study 5: Fruit and Vegetable Cold Storage in Cape Verde

Context: Island of Fogo, Cape Verde. Fruit and vegetable growers and marketers in the 2008 MCC Cape Verde Project implemented by Agland Investments http://www.mcc.gov/countries/capeverde/index.php.

Problem statement: How to reduce post-harvest losses of fresh fruits and vegetables during the marketing period and increase revenues for growers and marketers, when ferries from Fogo to the capital city of Praia (a 10-hour journey) are scheduled only two times per week?

Background: Produce on Fogo was harvested and packed on the farms, but not pre-cooled before shipping, and often had to wait one to two days for a ferry to arrive. Ambient temperatures range from 20°C to 35°C, and at times the ferry would be too full to take the fruits and vegetables as cargo, leaving these products on the dock to await the next ferry or be sold locally. Post-harvest losses under these conditions could on occasion reach 100% if the local market women known as rabidentes did not quickly find an alternative market.

Technology selected to address the problem: A small facility for three prefabricated walk-in 13°C cool rooms is currently being designed and constructed near the port of Sao Felipe, where vegetable and fruit marketers will be able to lease space for their packed crops on a per kg basis.The pre-cooling room is 5m x 6m in size and can handle up to 3 MT loads per day, and the cool rooms are 5m x 6m in size, each with a capacity of 8 to 9 MT. The price per kg will be set at the cost of electricity for pre-cooling and cold storage plus a small handling fee to help cover the $100,000 capital cost for the cool rooms (amortized over 20 years). Pre-cooling is estimated to require 30 to 35 kWh per MT and energy use for cold storage will be 20 to 30 kWh per MT per day (depending upon the average ambient temperature in Fogo, which varies by season).

Results: Reductions in post-harvest losses are expected to be considerable, and will more than cover the fees paid for pre-cooling and temporary cold storage. Consumer demand for cooled produce is high, but transport has been unreliable to date. Currently electricity rates are very high at US$0.35/kWh, so investment in wind power generators are under consideration as a potential alternative energy source

The pre-cooled Fogo crops arrive in Cape Verde for sale in local supermarkets. Post-harvest losses are significantly reduced via cooling and cold storage in Fogo prior to shipment.

Photo Credit: Lisa Kitinoja, 2008

Table 15 Approximate Refrigeration Capacity for Small-scale Cold Rooms

Size of Cold Room (m2)	Storage Capacity (MT)	Range of Refrigeration Capacity (MT of refrigeration)	
		Target = 1°C	Target = 13°C
10	3	1.0	0.75
20	6	1.5 – 2.5	1 – 1.5
40	12	3.5 - 4	2 - 3
60	18	5 – 6.5	3 – 4
80	24	6.5 – 8.5	4 – 5.5
100	30	7.5 -10	4.5 – 7

Source: Thompson and Spinoglio, 1996

The range of tons of refrigeration shown in Table 15 reflects the climate in which the cold room is located. A standard ton of refrigeration equals 12,000 BTU/ hr, equivalent to about 3.5 kW. The higher number in each range will be for the hottest times of the year or hot climates such as lowland tropics or semi-arid regions. Approximately 60% of the floor space is usable for storage, as the rest is taken up by doorways, aisles and open space left along the walls. A conservative estimate of energy use for cold storage electricity use is the 55 kWh/MT factor for forced-air coolers in California, since these operate in a relatively warm environment and handle large volumes of fruit each day.

The following measures will improve the energy efficiency of the cold storage facility:

- Reduce the effective wall temperatures by painting south-facing walls with white or light color materials;
- Reduce roof temperature by using light colored or reflective roofing materials (can reduce energy use by 3 to 4%);
- Reduce fan and lighting use;
- Increase insulation in the ceilings and walls;
- Consider external insulation with high thermal mass walls and floors;
- Seal any openings (especially around doors and windows);
- Use air curtains or plastic strip curtains to reduce heat infiltration into cold rooms by 70 to 80% (see Figure 30). Plastic strip curtains on cold room doorways, made of clear strips of PVC, can reduce heat infiltration from warmer areas into a cold room by 85 to 90%;
- Install extra heat exchange surface for the condenser in order to further reduce refrigerant condensing temperature;
- Ensure that the temperature of the refrigerant fluid after it is cooled in the condenser is as low as possible;
- Select evaporative condensers rather than air-cooled units;
- Maintain highest possible suction pressure to reduce compressor energy use;
- Use high efficiency motors, and select 2 or 3 speed motors whenever possible so the lowest speed can be used as conditions allow.

Figure 29 Plastic Curtains to Keep Cold Rooms Cold

Photo Credit: EnviroBarrier; http://www.envirobarrier.com

Evaporator fan controllers: With assistance from the Department of Energy's Inventions and Innovation Program, Advanced Refrigeration Technologies (ART) has commercialized an innovative control strategy for walk-in cooler refrigeration systems. The ART Evaporator Fan Controller is inexpensive ($100 to $300) and easy to install. Overall, the ART reduces evaporator and compressor energy consumption by 30% to 50%.

Back-up generators matched to power needs of cold rooms: The cost of new engine-driven generators varies with generator size. A 100 kWe unit costs about $150 to $200 per kWe. Smaller units will cost more per kWe. A 30 kWe unit, for example, may be priced at $400 per kWe. Installation and transfer switches are additional costs.

Diesel engines consume about 0.4 pounds of fuel (about 0.21 liters) per hour per output horsepower. A 100 kW generator requires a 200 horsepower engine. If the engine operates at 50% output, it will consume 40 pounds of fuel (about 5.6 gallons or 21 liters) per hour.

Renewable Energy-powered Technologies

Back-up generators: These may be run using bio-diesel or alternative fuels. Diesel engines and gensets that are designed to operate on vegetable oil (such as Jatropha oil) are commercially available and bypass the need to convert vegetable oil to a true biodiesel fuel.

PV-powered evaporative cooling: Evaporative coolers are available that use photovoltaic (PV) panels to generate the electricity used to run the blower and the water pump. For hot desert areas the combination of evaporative cooling and solar power is an excellent match. In the afternoon, when the most solar energy is available, it is the hottest part of the day, when cooling is needed most. Since swamp coolers use a small fraction of the energy of air conditioners, PV panels can provide sufficient electricity to run the system effectively.

Solar chiller: Commercial PV-powered refrigerators have been developed for medical refrigeration. These are powered by a 3 x 60W PV array, with ice as the energy storage medium (in a double-walled system). Batteries rather than ice may also be used. These units were developed primarily for medical purposes, to maintain the cold chain for heat-sensitive medicines. The cost is estimated at less than $2,000 for a unit that has a storage capacity of 50 to 100 liters. These units could be used for short-term storage of highly perishable high-value crops. A careful cost-benefit analysis should be conducted to determine if the cost of a solar refrigerator is justified on the basis of increased revenues and profits resulting from lower product losses and better quality in the delivered product. A very high efficiency PV-powered refrigerator with 200 liter capacity is available from SunDanzer and requires only an 85 W PV module (http://www.partsonsale.com/sundanzer.html).

The following table gives some comparative details regarding the costs of various cold storage options and cold storage operation technologies. Approximately 35% to 40% of the energy use for cold storage is used to keep produce cool, while the remainder is used to remove the heat coming into the facility from solar radiation, warm air infiltration, fans, lights, people, and other equipment, so any measures to reduce heat load will help reduce energy use.

Table 16 Cold Storage Technology Characteristics

Cold Storage Technology	Purchase Price or Construction Cost	Typical Capacity (MT)	Energy Use Per MT	Estimated Max. Energy Use/Day
Bricks and sand evaporative cool box	$200 to 300	0.2	0	0
Evaporatively cooled storage room 20 m^2 floor area	varies	5 to 6	0.09 kWh	0.45 kWh to 0.54 kWh
Evaporatively cooled storage room 40 m^2 floor area	varies	10 to 12	0.09 kWh	0.9 kWh to 1.2 kWh
Ventilation fan for night air cooling	$200 to $300	varies	100 watts/hr (8 hour night)	0.8 kWh
New prefabricated cold room 20 m^2 floor area	$20K	6	50 kWh for 4°C or 30 kWh for 12°C	300 kWh or 180 kWh
New prefabricated cold room 40 m^2 floor area	$32K	12	50 kWh for 4°C or 30 kWh for 12°C	600 kWh or 360 kWh
Used prefabricated 20 m^2	$4K to $12K	6	50 kWh for 4°C or 30 kWh for 12°C	300 kWh or 180 kWh
Used prefabricated 40 m^2	$7.2K to $21K	12	50 kWh for 4°C or 30 kWh for 12°C	600 kWh or 360 kWh
Cold room (small scale, owner built) 20 m^2	$4K to $8K	6	50 kWh for 4°C or 30 kWh for 12°C	300 kWh or 180 kWh
Cold room (small scale, owner built) 40 m^2	$7.2K to $15K	12	50 kWh for 4°C or 30 kWh for 12°C	600 kWh or 360 kWh
Cold room (small scale, owner built) 60 m^2	$10.8K to $22.5K	18	50 kWh for 4°C or 30 kWh for 12°C	900 kWh or 540 kWh
Refrigerated cold room 80 m^2	$14.4K to $30K	24	50 kWh for 4°C or 30 kWh for 12°C	1200 kWh or 720 kWh
40 foot reefer retrofit – 25 m^2 (used highway van or refrigerated marine container as 4 C cold room)	$24K to $32K	7	40-48kWh or 3.5 to 5.0 L/hour	280 kWh to336 kWh or 84 L to 120 L diesel fuel
20 foot reefer retrofit – 12 m^2 (used highway van or refrigerated marine container as 4 C cold room)	$12K to $16K	3	40-48kWh or 2.2 to 4.0 L/hour	120 kWh to144 kWh or 53 L to 96 L diesel fuel
Back-up generator 100 kW	$15K to 20K		21 L/hour diesel fuel	
Back-up generator 400 kW	$60K to 80K		84 L/hour	
Back-up generator 800 kW	$120K to 160K		168 L/hour	

Assumptions: 1) Cold storage rooms (operated either at 4°C for temperate crops or 12°C for tropical crops) are used at or near full capacity.
2) Energy costs per MT will increase in proportion to the percentage of unoccupied space.
3) Back-up generators would need to be operated for only a few hours.

Source: Information compiled by Lisa Kitinoja

Chapter 4: Drying of Produce

Another way to add value to fresh fruits and vegetables is to dry produce before packaging and marketing. Drying perishable commodities can greatly extend product shelf life and reduce post-harvest waste, as well as greatly reduce transportation and storage costs. Drying of fresh produce, which contains up to 95% water, to a safe moisture content of 7% to 8% requires the application of low heat and ventilation for the best results. The estimated time required for drying will vary based upon the type of fresh produce.

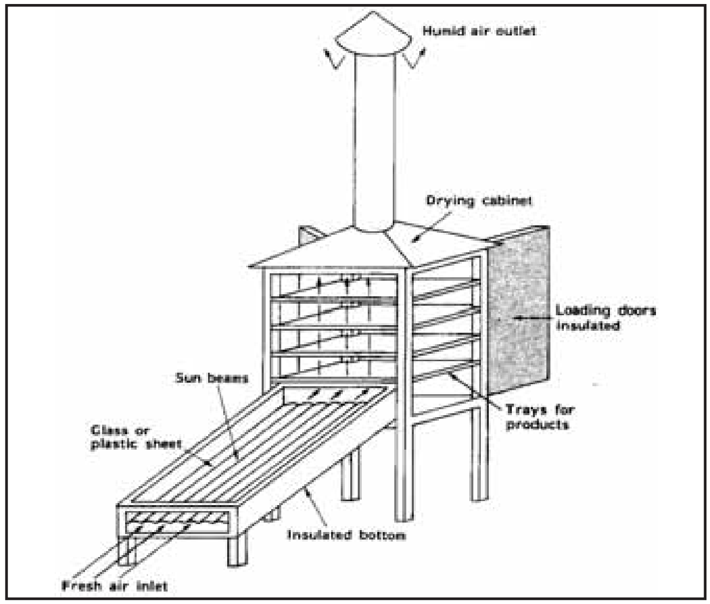
Manual/low-tech Technologies

Preparations: Peeling, cutting, or slicing produce into uniformly sizes pieces is usually required for successful drying. Typically this is done by hand.

Direct solar drying: Laying produce out in the sun to dry naturally is common in sunny climates and is a very inexpensive drying method. It is still the predominant method for producing raisins throughout the world. However, the temperature may become too high, causing heat damage, or the weather may change quickly, and rain can damage the product. Direct solar-dried produce tends to turn brown and dry unevenly. In addition, insect, bird, and rodent pests can easily attack the produce.

Indirect solar drying: As shown in Figure 31, indirect solar drying requires a covered dryer that protects produce from direct sunlight while capturing more heat from the sun, with air flow inside an indirect dryer to reduce the chances of heat and pest damage while speeding drying.

Figure 30 Indirect Solar Dryer



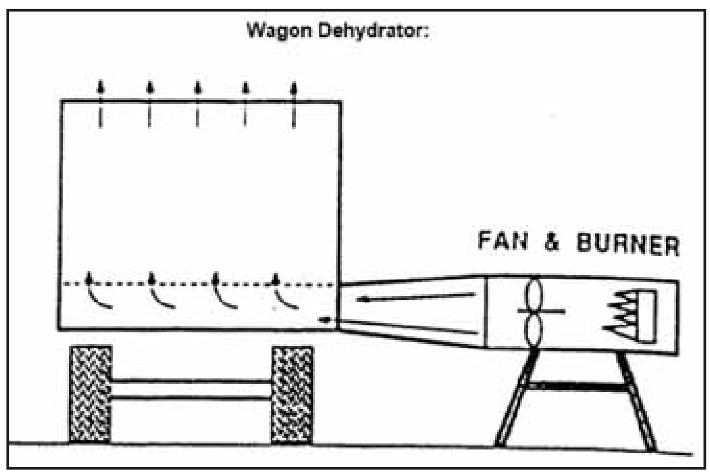
Source: FAO, 1985

Fossil fuel-powered Technologies

Preparations: Machines are available to speed the peeling, cutting, or slicing of produce into uniformly sized pieces, which is usually required for successful drying. Blanching (a pre-treatment recommended for enhanced quality which is required for successful drying of many crops) requires cut fruits be placed into steam or boiling water for a short time period of time (typically 3 to 5 minutes).

Heat-assisted drying: In rainy weather or humid locales, heat-assisted dryers create warm air flow inside the dryer to speed drying. Heat sources may be electric, propane, wood, or any other locally available fuel. Appropriate drying temperatures (60°C for prunes, 54°C for other fruits and vegetables, 32°C for herbs and parsley, 43°C to 54°C for walnuts and almonds, respectively) can easily be achieved with low-powered, relatively inexpensive technologies (see Figure 32 and Case Study #6).

Figure 31 Heat-assisted Batch Dryer



Source: Thompson (2002) in Kader

The majority of energy use in heated air dryers is for heating air. Electricity for air moving is only a small fraction of the air heating costs. Air heating costs vary depending on the initial and final moisture contents of the product. If energy conservation measures such as air recirculation are incorporated into the operation, fuel use can drop significantly.

Table 17 provides comparative details regarding the energy requirements for various drying methods and associated drying technologies. Cost variations are based on throughput. If units are not utilized at full capacity, costs per MT can increase considerably.

Table 17 Energy Requirements for Drying Agricultural Products

Drying Technology	Typical Capacity	Energy Use (kWh, liters or BTU)/MT
Direct solar drying	0.5 MT	0
Indirect solar drying	1.0 MT	0
Heat-assisted drying (small scale)	< 2 MT /day	6 kWh and 2,300 MJ
Heat-assisted drying (intermediate scale)	2 to 5 MT/day	6 kWh and 2,300 MJ
Heat-assisted drying (large scale)	>5 MT/day	6 kWh and 2,300 MJ (57.8 L diesel)

Source: Kitinoja and Gorney, 1999

Case Study 6: Drying Fruits and Vegetables in Western Cameroon

Context: Fruit and vegetable growers in Western Cameroon, under the 2008 USDA Food for Progress Program, implemented by Winrock International.

Problem statement: How to reduce food losses and increase revenues for vegetable and fruit growers in the humid highlands of Western Cameroon?

Background: Agricultural production throughout Cameroon's northwest and western provinces is highly intensive, producing a variety of foods for markets in large urban areas as well as neighboring countries. Within the region, the ability to process and prolong the shelf life of agricultural goods is limited. Many producers are forced to sell their harvest during peak periods at a loss, due to the inability to preserve their fresh produce. In market-places, goods can be found rotting due to the overabundance of production. A dryer capable of producing high-quality dried fruit and vegetables allows producers greater control over produce prices, as well as access to more distant and lucrative markets.

Technology selected to address the problem: Winrock International has developed a low-cost, medium-sized ventilated gas dryer to assist producers in the high quality drying of numerous agricultural products (e.g., peppers, spices, greens, medicinal plants, fruits, mushrooms, meat, and fish). The dryer has a drying space of $5m^2$ and uses an innovative ventilation system that allows users to control air circulation throughout the drying process. Such control over air circulation allows for efficient energy consumption and produces high-quality finished dried products. The dryer is constructed using locally available materials, thus permitting Winrock to train local manufactures in the construction and maintenance of the dryers. Assuming the processing of one ton of fresh peppers a year, approximately $2,000 in net income will be generated, more than three times the capital investment made in the dryer.

Results: Winrock has trained three local metal manufacturers in the construction of the dryer technology. Trained in dryer operation, three small enterprises are currently drying for sale a variety of local crops, including fruits, peppers, ginger, greens, and other specialty products. Spice producer and dryer Pius Chifontah of Vinji Spice says, "Before the introduction of the dryer, drying the pepper from my farms was nearly impossible due to the rains and the inefficiency of sun drying in the region. Now, I dry my pepper during the peak production season and my ginger during the following season. I am already packaging, marketing, and selling my transformed products throughout the region."

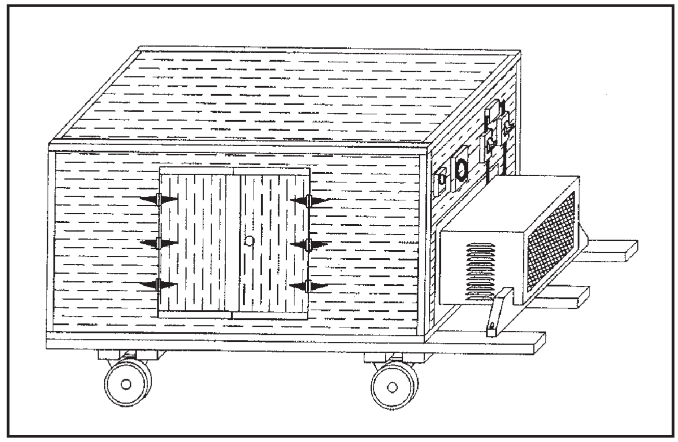
The innovative ventilation system (shown below, left) has helped Vinji Spice (at right) dry its products quickly and efficiently.

Photo credits: Andrew Kovarik

Chapter 5: Transport of Horticultural Products

Transport occurs many times within the horticultural value chain. Transportation is required to move produce from the field to the packinghouse, from the packinghouse to the cold storage, and from the cold storage site to the port (for exports), wholesale market, or local destination retail marketplace (for domestic sales). Exports will require additional land, air, or sea transport. Manual technologies for transportation consist largely of animal-powered vehicles, carts, or wagons. Fossil fuel-powered technologies, in contrast, incorporate a wide range of transportation modes.

Figure 32 USDA Porta-cooler



Source: FAO http://www.fao.org/docrep/009/ae075e/ae075e20.htm

Figure 33 Small Reefer Truck

Photo Credit: Kitinoja (2001)

Porta-coolers, or insulated boxes fitted with air conditioners and diesel generators, can be carried on traditional vehicles (pick-up trucks, flatbed trailers). A small insulated box (3.5 m^3), holding approximately 700 kg of produce, fitted with a room-sized air conditioner (10,000 to 12,000 BTU) and diesel-powered generator (2 kW), can be pulled as a trailer (USDA Porta-cooler, 1993) or set into a pick-up truck bed (see Figure 33). Water loss can be reduced by using plastic liners in containers.

These units can be operated successfully at temperatures of 10°C or above with good results, making them most useful for transporting tropical and sub-tropical horticultural crops. Room air conditioners are not designed to operate efficiently at very low temperatures and produce low relative humidity, cooled air that can cause unacceptably high rates of water loss during cooling of fruits and vegetables. Furthermore, at temperatures below 10°C, ice will build up on the coils, and the air conditioners will not work as designed.

In many situations an evaporative cooler will be a less expensive and better performing option for the porta-cooler. The evaporative cooling unit can replace the air conditioner in the design, and a deep-cycle battery can supply the power to run a small water pump (1 L per minute, requiring 10 watts or less) and a 100 to 200 watt fan for moving air through the wet pad of the cooler. The interior of these cool boxes are 3.5 to 7.0 m^3, and the fan needs to be able to provide one air exchange per minute and move the air against a static pressure of 0.6 cm w.c. (approximately 64 to 128 CFM). An exit vent must be provided at the back of the load to allow the evaporatively cooled air to move completely through the load inside the insulated box. If the unit is on a truck, it can be fitted with an air scoop above the cab to force air through the unit when the truck is moving so the fan power is required only when the unit is stationary.

Cold trucks, also known as reefers, come in various sizes. The most common cold trucks are 12 ft and 20 ft reefer trucks with a diesel generator for powering the refrigeration system (see Figure 34). These can carry up to 6 pallets (smaller reefer) or 10 pallets supporting 800 kg of produce apiece. Since the refrigeration system installed on a cold truck is relatively small compared with the size of the vehicle's engine, it should contribute a relatively small increase in fuel use for the total transport energy use. A reasonable estimate is that a refrigerated vehicle would use 5% to 10% more fuel to carry the same load over the same distance.

According to ThermoKing, marine containers or inter-modal reefer containers require 5.0 to 6.5 kW of electric power per hour to run their refrigeration units (via plug-ins on the ship and in ports during delays before loading or pick-up). New models can be much more energy efficient, requiring only 3.6 to 4.0 kW for refrigerating the same size loads. About 80% of reefers in Europe have an electric standby option that allows the unit to be plugged into electric power, improving fuel efficiency by up to three times that which can be achieved by using diesel power alone.[9] Estimates of 2.2 to 5.0 liters of diesel fuel per hour are required for operating a generator unit on typical 20-foot to 40-foot reefer containers, with total fuel consumption rate depending upon the set temperature. Air freighters are usually not equipped with refrigeration equipment.

There are surprisingly few comparisons available of the energy use for different methods of transport. The most current comprehensive study is from Europe (van Essen et al. 2003) for non-refrigerated transport, which is the basis for Table 18 below, showing energy consumption for various transport methods. Small highway vehicles, particularly cars used for hauling small amounts of produce, are much less energy efficient than large trucks. Rail transportation is estimated to be about three times more energy efficient on average than trucking, making this mode particularly attractive as fuel costs rise. Marine transport is the most efficient transport mode.

Table 18 Energy Consumption for Various Transport Methods

Transport Method	Energy Consumption (MJ/MT-km)
Passenger car (diesel powered w/ 100kg of produce on various road types)	23.2 – 13.4
Air freighter (500 km trip)	10.2
Air freighter (6000 km trip)	6.8
Highway van (<3.5 MT capacity)	8.04
Highway trailer (>20 MT capacity)	0.86
Train (diesel powered, 790 MT capacity)	0.56
Sea vessel (container ship w/ 3,500 MT capacity)	0.30
Sea vessel (container ship w/ 4,000 MT capacity)	0.18

Source: Calculated from data obtained from van Essen et al, 2003

Table 19 compares income generated with the traditional transport practice versus an improved practice whereby the produce is pre-cooled using forced air cooling. The example using actual data from Ghana results in increased income of 25 percent (see Case Study #7 and Case Study #8).

Table 19 Cost/Benefit Worksheet for Okra Exported from Ghana to the EU (2002)

Assume Harvest 1000 kg	Traditional Practice	New Practice
Description of practice	No cooling Air ship	Pre-cooling via forced air cooling Air ship
Difference in costs		
$0.04/kg cooling cost		$0.04 x 1000 = $40
Relative cost (considering only the added costs for the new practice)		+$40
Expected benefits		
% losses	10%	2%
Amount for sale	900 kg	980 kg
Value/kg	$1.00/kg	$1.30/kg
Total market value	$900	$1,274
Market value – added costs	$900 – $0 =$900	$1,274 – $40 =$1,234
Relative profit per 1000 kg load (difference in market value)		+$334

Source: Unpublished data from USDA Ghana CCARD Project, Kitinoja (2002)

9 See www.trucknews.com

Case Study 7: Transportation of Perishables in Ghana

Context: Vegetable export marketing group in Ghana, 2001-02. (USDA US-Ghana CCARD Project) http://www.rurdev.usda.gov/rbs/pub/may04/ghana.htm

Problem statement: How to reduce losses of vegetables produced for export and increase revenues for growers and marketers in Ghana?

Background: Post-harvest losses for the delicate vegetable crops of okra and long beans were as high as 50% when marketers transported vegetables at ambient temperatures from farming areas to the Accra port for air shipments to international markets. Water losses alone were estimated to be in the range of 10 - 15% per day (as measured by weight changes) and fungal problems were common, leading to a high percent of rejects at the terminal markets.

Technology selected to address the problem: The marketing group developed a $1,600 model refrigerated trailer equipped with a 12,500 BTU air conditioning unit and a 2,000 watt diesel generator to pick up and transport packages of vegetables from one dozen member farms. The ambient temperatures ranged from 30° to 40°C and the portable cooler was set at a target temperature of 15°C. The energy for refrigeration during 12 hours of cool transport of 0.5 MT of vegetables is provided by 12 L of diesel fuel at a price of US$0.75 per liter (current prices are similar to those in 2002 as energy supplies in Ghana are organized as a state monopoly).

Results: Postharvest losses were reduced to less than 5%, market value as assessed by buyers was improved, and the percentage of rejects was reduced. Returns were much higher than the cost of operation, and the capital costs for each portable cooler can be recovered after only 16 to 20 loads (depending upon the value of the crops being transported).

Case Study 8: Transportation of Perishables in India

Context: Guava marketing company, Gujarat, India, 2001-2002. (APEDA Postharvest Management Program) http://www.apeda.com/apedawebsite/index.asp

Problem statement: How to reduce losses of guavas during shipping, to increase revenues for growers and marketers in India?

Background: Post-harvest losses for the delicate guava fruit crop were as high as 40% when marketers tried to transport bulk loads of ripe fruit in leased open trucks at high ambient temperatures on a two day long journey from Gujarat to the central wholesale market in New Delhi.

Technology selected to address the problem: The marketing company in Gujarat leased a 20-foot refrigerated trailer truck and used vented plastic crates to transport 10 MT of guavas at a target temperature of 12°C. The energy used for refrigeration during the two days of transport was provided by 100 L of diesel fuel (approximately 2L per hour) at a price of Rs20 per liter (equivalent to US$0.50/L; 2008 prices are approximately Rs30/L under government subsidies).

Results: Post-harvest losses were reduced to 10% and the operation was immediately profitable, since the extra cost for providing refrigeration was less than $5 per MT. After two seasons the company had made enough profits to purchase two used refrigerated trailer trucks and no longer had to pay to lease vehicles. In this case, even with the higher fuel prices experienced in 2008 (at an estimated cost of US$7.50 per MT) the use of refrigeration during transport would be highly profitable.

Chapter 6: Biomass-based Fuels for Shaft Power, Electricity, and Process Heat

The previous sections have described a number of renewable energy technologies and their application to horticulture, as an alternative to the use of conventional fossil-fueled engines and thermal energy units.

This section discusses two additional options for alternative energy. One is the production of liquid fuels from indigenous plants and agricultural crops. The other is the use of biomass residues to power biomass gasification units that produce both heat and electricity (combined heat and power, or CHP).

Renewable Liquid Fuels

Renewable liquid fuels include biomass-derived ethyl alcohol (ethanol) and biodiesel (derived from various types of vegetable oils). In the United States most gasoline is 10% ethanol by volume, and there are gasoline engines designed to use gasoline/ethanol mixtures ranging from pure gasoline to pure ethanol. Vegetable oils may be used for powering some diesel engines that are designed for such oils. Biodiesel fuels are made from vegetable oils in a process known as trans-esterification. Such fuels generally can be used interchangeably with petroleum diesel.

The liquid fuels option sometimes requires the large-scale cultivation and processing of a crop to produce the renewable fuel economically. Important examples can be found in the production of ethanol from sugar cane, corn, cassava, or sugar beet and the production of biodiesel from plant oils (e.g., palm oil, coconut oil, Jatropha oil, and other seed crops). In other cases, the renewable fuel may be produced on a small scale, often in association with a farmer's other horticultural crops. In either case, the principal objective for the farmer is to reduce the cost of motive power, electricity, and heat, and to increase the reliability of adequate affordable energy supplies. In many countries, national government objectives for renewable fuels include the reduction in foreign exchange expenditures on imported fuel, reduction of carbon dioxide emissions, and increases in both national energy security and local employment.

Until recently few renewable liquid fuels have been able to compete without subsidies, either because the production of the crop feedstock, or the refining needed for good operational performance, or the combination of these factors rendered the renewable fuel more expensive. The recent increase in petroleum fuel costs, as well as concern over global carbon emissions, have led both the public and private sectors in many countries to invest heavily in increased production and processing of renewable fuels, mainly ethanol from sugar and corn, and also in production of biodiesel from palm oil and other vegetable oils.

Important advantages of biodiesel over natural vegetable oil when used as an engine fuel are that (1) it may be blended with diesel fuel in virtually any ratio, and (2) it can also be used directly without a noticeable difference in engine operation. A diesel engine will not start with natural vegetable oil unless the engine is already warm, due to the high viscosity of the oil, which interferes with its vaporization. In very warm climates, such as much of sub-Saharan Africa or the Pacific Islands, vegetable oils often can be used in engines without the preheating requirements. A diesel engine that is set up to burn natural vegetable oil must have a second small fuel tank with diesel fuel to start the engine, and must also have a fuel heater or fuel filter heater to ensure that the naturally occurring waxes in vegetable oil do not quickly clog the fuel filter.

For stationary (non-vehicle) engines, the use of pure vegetable oil may be an attractive option. This avoids the somewhat dangerous biodiesel conversion process and will yield more energy per gallon of vegetable oil consumed. However, some diesel engines and the highly efficient direct-injected diesel engines in particular, require periodic cleaning of their injectors when fueled with vegetable oil. Using pure vegetable oil requires greater engine maintenance, requiring a higher level of mechanical skill, than when biodiesel fuel is used. Several Pacific Islands nations, such as Vanuatu, have been using refined coconut oil as a fuel source in both mobile and stationary diesel engines, and find the additional maintenance requirements worthwhile given the savings in petroleum fuel costs.

Another relatively minor issue with both alcohol- and vegetable oil-based fuels, including biodiesel, is that the rubber fuel hoses that are normally used for gasoline and diesel must be replaced with non-rubber hoses. The oxygen present in alcohol and vegetable oil causes rubber to soften, swell, and eventually disintegrate. Hoses may be satisfactorily replaced with Teflon, which is expensive, and also with certain synthetic rubber-like compounds. Since a fuel line failure can result in an engine catching fire, especially with a spark ignition engine, it is essential to ensure that vehicles and engines that will be powered by renewable fuels have been properly equipped.

Most diesel engines are warranted for operation on a mixture of petroleum diesel and biodiesel fuels, with the manufacturer specifying the allowable range of mixtures (usually up to 10% to 20% biodiesel). Few such engines are designed to operate from vegetable oils. Small (<20 kW) Lister-type diesel engines are designed to operate using biodiesel fuels, and are increasingly used to power multi-function platforms used in West Africa. These mobile platforms combine a small diesel engine with belt-driven equipment that typically includes a generator (for battery charging), a grain grinder, a grain miller, and in some cases a water pump.

Many mechanized agricultural and horticultural operations such as grinding and milling are far more efficient and far less labor intensive than manual methods. Table 20 compares manual corn grinding with mechanized corn grinding with a Jatropha oil-fueled engine. This example shows the labor savings associated with a renewable fuel. However, some harvesting operations necessitate manual labor to maximize ripeness and quality of the product.

Table 20 Energy and Power Requirements for Milling 100 kg of Corn

Power and Time Requirements	**Manual Corn Milling**	**Mechanized Corn Milling (Jatropha oil)**
Power required per kg of corn/hour	50 watts	50 watts
Power of one person	50 watts for several hours (healthy adult) 100 watts for 5 – 8 hours (trained athlete)	
Power of 10 hp motorized mill		5,000 watts
Jatropha oil consumed	none	2 liters
Time Requirements		
Time to pick 8 kg Jatropha seed	none	8 hours
Time to press Jatropha seed (hand press)	none	2 hours
Miscellaneous labor (Jatropha seed drying, etc)	none	4 hours
Total time (labor)	**50 hours**	**16 hours**

Source: Winrock International

A similar comparison for pumping water for the purpose of irrigating one hectare of land is shown in Table 21.

Table 21 Energy and Power Requirements for Water Pumping to Irrigate 1 ha of Land

Power and Time Requirements	Treadle Pump	Diesel Centrifugal Pump (Jatropha oil)
Power to raise 2.5 m3/hour from 6m depth	100 watts	100 watts
Power of person	50 watts for several hours (healthy adult) 100 watts for 5 – 8 hours (trained athlete)	
Power of 5 hp diesel pump		2,500 watts
Jatropha oil consumed	none	1 liter
Time Requirements		
Time to lift 100 m3	20 hours	1.6 hours
Time to harvest Jatropha seed	none	4 hours
Time to dry Jatropha seed, etc.	none	2 hours
Time to press Jatropha seed	none	1 hour
Total time (labor)	**20 hours**	**8.6 hours**

Source: Winrock International

Such comparisons have to be verified for a particular environment, where such conditions as the yield and abundance of Jatropha trees, and the quality (oil content) of the seed will have a major impact upon the labor savings. The comparison does not take into consideration the fact that the labor required for hand pounding corn or for operating the treadle pump requires strength and exertion, while only the labor required to operate the hand press requires significant effort in the case of Jatropha. Hand picking and drying seeds may be done by children or the elderly.

Challenges to Successful Use of a Renewable Liquid Fuel: The Case of Jatropha

Figure 34 Two-year-old Jatropha Plantation in India

Photo Credit: http://www.treeoilsindia.com

A plant that has received widespread attention as a source of renewable liquid fuel, and which appears less likely than others to compete with the food supply, is Jatropha curcas. Jatropha[10] is a small tree or bush that grows to a height of 3 to 5 meters in most tropical countries, and survives in arid climates and poor soils. Jatropha seed is inedible and, except for limited use in soap making and for wick lanterns, it has not been widely harvested. Because Jatropha is a perennial, it does not need to be replanted, requiring less labor from farmers. An added bonus is that Jatropha plants help protect the soil from erosion.

Jatropha is often planted by farmers as a hedgerow in parts of South and Central America, sub-Saharan Africa, and Asia. These hedgerows are effective in separating cattle from homes and gardens because cattle have learned to avoid Jatropha due to its toxic properties. It is considered to be an excellent candidate for the production of biodiesel fuels. Many thousands of hectares of Jatropha have been planted in recent years in a number of tropical and sub-tropical countries (e.g., India, Philippines, China) with the expectation of reducing diesel fuel imports or producing a renewable fuel for export to those countries that pay a premium for renewable fuels (see Figure 35). For a number of reasons, however, Jatropha may not deliver the anticipated yields and benefits that are often attributed to it. The Jatropha story serves as a good example of the prudence and attention to detail that is needed in designing a project to promote renewable fuels.

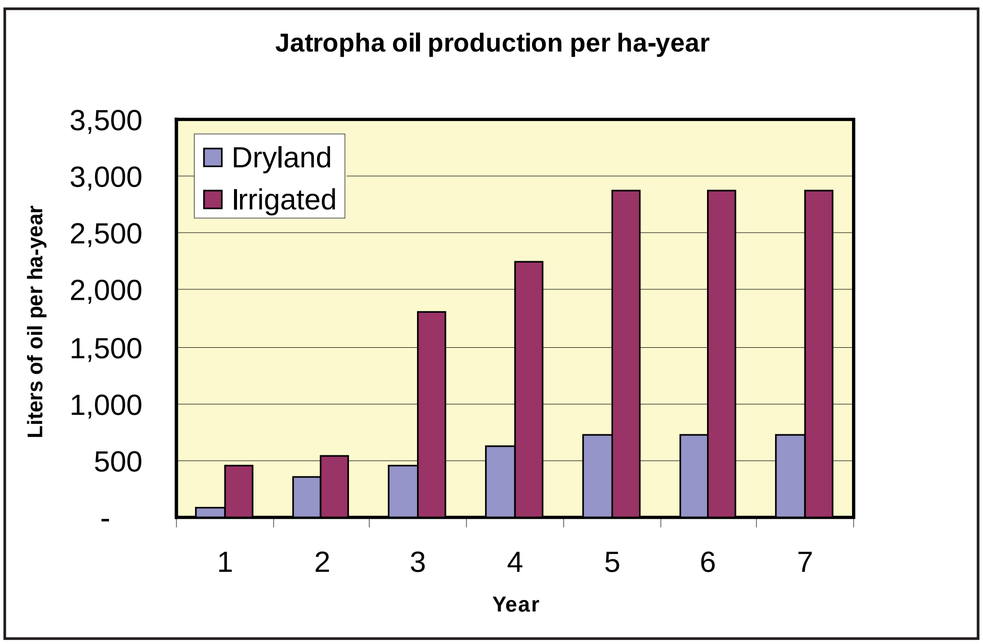
10 See, for example: http://www.jatrophabiodiesel.org/openIssues.php, http://www.svlele.com/jatropha_plant.htm, http://www.i-sis.org.uk/JatrophaBiodieselIndia.php

Despite the favorable comparison of a Jatropha-fueled engine against direct use of muscle power, it is necessary that Jatropha meet the more difficult test of being cheaper than diesel. Previous experience suggests that, with manual picking and pressing of the seed, the price of one gallon of diesel must be greater than the value of two days' labor in order for Jatropha to compete. This condition now prevails in many African countries. Despite this, several factors can adversely affect the performance of Jatropha, and therefore discourage farmers from using this technology:

- Jatropha may yield poorly due to unsuitable soils, low rainfall and low water table, and insect pests. Annual oil production will increase until about the third or fourth year of cultivation, after which it is fairly steady for another 10 or more years. The productivity depends strongly on both soil nutrients and water;
- Jatropha must be harvested and the seeds dried promptly at maturity to avoid loss of oil content to fungi either before or during storage;
- Rain-fed Jatropha will yield most of its seed during the rainy season, when drying will be difficult;
- Poor quality seed will give a very low oil yield, increasing the cost of the oil due to the larger quantity of seed used and high labor demand and low productivity of the press.

The practical issues associated with Jatropha cultivation, harvesting, drying, and processing are challenging. Some well-funded projects that attempted to encourage farmers to grow large plantations of Jatropha have underestimated these challenges, and also exaggerated yields and other factors, and provided generous credit in order to convince farmers to participate.

Figure 35 Jatropha Oil Production



Source: www.jatrophabiodiesel.org

Jatropha is not a high-value crop, unlike coffee or cacao. Its seed must be very inexpensive in order for the oil to compete with diesel fuel. The Jatropha production system must be easy to manage and must be tied to efficient local processing of the seed. Local processing reduces transport costs and storage losses, while enabling the processors to exercise a role in helping farmers to improve seed quality. Jatropha seems most likely to succeed when planted as hedges surrounding horticulture or other irrigated crops (see Figure 36). Properly managed Jatropha hedges should provide enough oil to fuel diesel irrigation pumps on quarter hectare fields if the depth of the water table does not exceed approximately 10 meters. The seed cake or residue after extracting Jatropha oil can serve as a rich fertilizer, doubly benefiting the farmland and farmers.

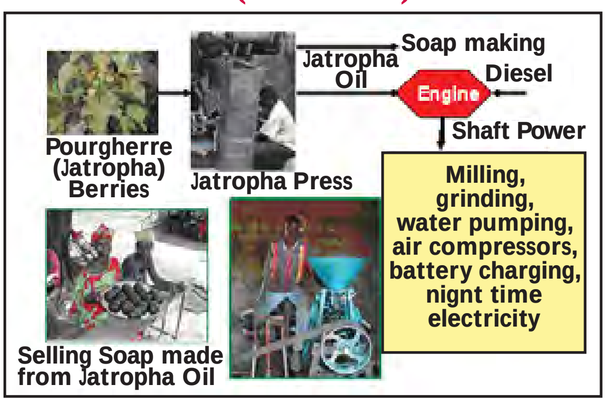
The Jatropha system described above assumes direct use of Jatropha oil to fuel diesel irrigation pumps. However, most projects will attempt to channel Jatropha production to medium and large scale facilities for producing biodiesel. The challenge here is to make this profitable for the farmer, the transporter, the processor, the distributor, and the consumer. Strong technical support to farmers, and preferential pricing for good quality seed are needed to bring down costs. It is essential to test production parameters on small scale demonstration plots, and to master seed harvesting, drying, and storage, before encouraging farmers to ramp up production.

The Multi-Function Platform, Fueled by Jatropha Oil

The small-scale use of Jatropha as a source of a fuel oil has special importance for small farmers in West Africa, and the example is in principle replicable widely in the developing world. This application uses Jatropha to fuel small (10 HP) diesel engines that drive a multi-function platform[11] and produces high-quality soap as well as biodiesel fuel (see Figures 37 and 38). It is especially important for women, as small groups of women have become owner-operators of these units in West Africa through the support of the United Nations Development Programme (UNDP) (see Case Study #9).

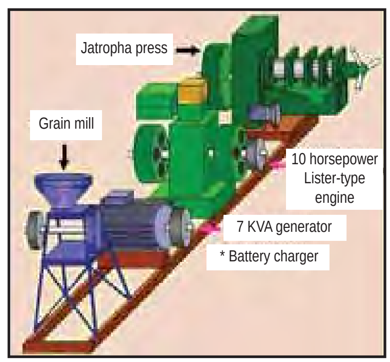
The multi-function platforms supported by the UNDP in Mali and elsewhere in West Africa are saving women substantial time and human energy, and are contributing directly to increased local incomes of women's groups that own and operate these platforms (UNDP 2004). The UNDP notes that "in the village of Noumoula (Mali), women compared hand production of Shea butter using the multifunction platform." The daily production increased from 3 kg to 10 kg, with a decrease of time per kg of a factor of 2 to 3. The use of the platforms generates immediate cash flow.

Figure 36 Multi-function Platform in Mali (West Africa)



Source: Mali-Folke Center for Renewable Energy
http://www.malifolkecenter.org/

Figure 37 Multi-function Platform Structure



Source: Mali-Folke Center for Renewable Energy
http://www.malifolkecenter.org/

11 For links to reports on the multi-function platform, see http://en.wikipedia.org/wiki/Multifunction_platform

Case Study 9: Jatropha Oil as Renewable Fuel Source for Multi-function Platforms in West Africa

Problem statement: How to provide electricity and shaft power to support small-scale farming and horticulture in West Africa using primarily non fossil-derived liquid fuels.

Background: Women in West Africa need electricity and motive power (shaft horsepower) to increase productivity and quality of fruits, vegetables, and other crops produced on a small scale for local markets and local consumption. Jatropha is a drought-resistant small tree that is widely used as a living fence. The seed is about 30-35% oil, and the oil can be used to fuel small diesel engines designed to use vegetable oil. Traditionally the seed has been harvested by women and used for medical treatments and local soap production.

Technology selected to address the problem: The technology combines local production of non-edible vege-table oil from Jatropha curcas with the multi-function platform (MFP) introduced by UNDP in Mali in the 1990s. The MFP integrates a small (10 HP) Lister-type diesel engine, retrofitted to use vegetable oil as fuel, with a battery charger, grain grinder, oil expeller (to expel oil from the Jatropha seed), and generator (7.5 kVA) for local evening electricity supply for lighting. Each specialized piece of equipment is belt-driven from the engine. The belts are quickly changed depending on the desired function. Other functions of the MFP include a compressor (for inflating tires for donkey carts and vehicles) and electricity supply for powering tools and welders for workshops. Locally, Jatropha planting is being expanded beyond the living fence function to provide oil for running the MFPs. The Mali-Folke Center for Renewable Energy (MFC) has led the practical development of Jatropha for local fuel oil production and the improvement of the MFP design and reliability, through engineering and through maintenance support. In 2008 the Bill and Melinda Gates Foundation provided a grant of $19 million to the UNDP to support expanded empowerment of women and increased agricultural/horticultural productivity in West Africa through the use of the MFP.

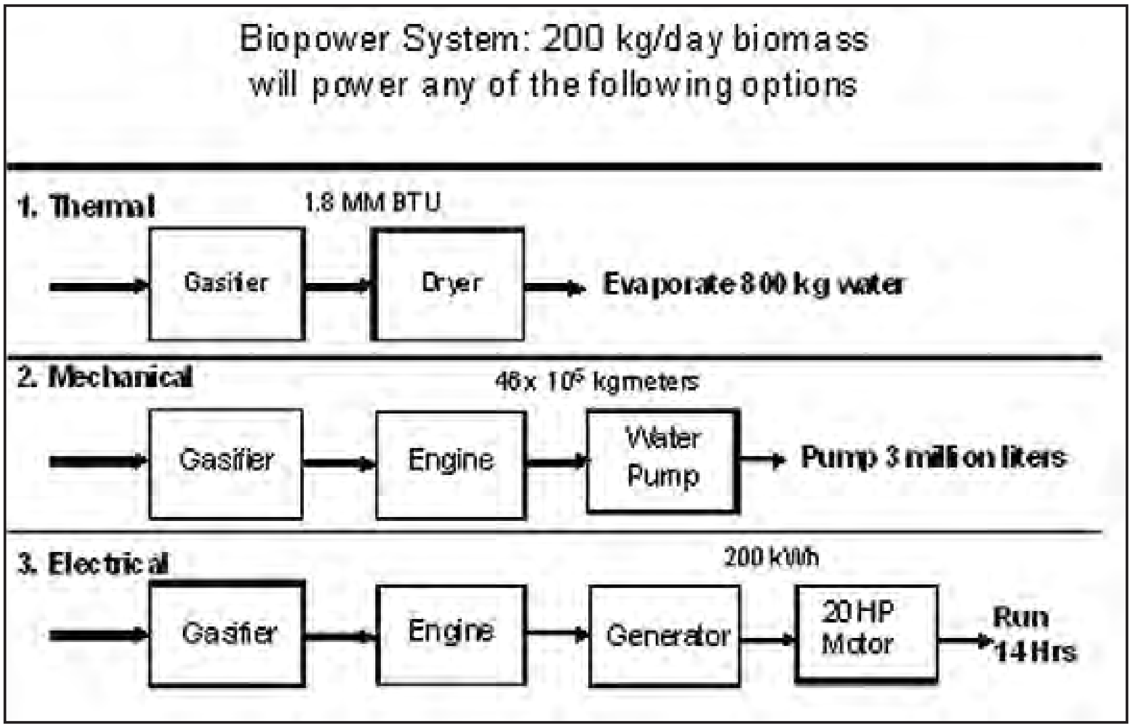
Results: The platforms are owned or leased by small groups of women in rural villages. UNDP and other groups have shown that labor and time requirements for basic agricultural and horticultural activities are greatly reduced compared with manual labor, and that incomes increase substantially with the use of the MFPs. According to the Global Energy Network Institute (November 2008):

> **"The platform frees up two to six hours of a rural Malian woman's day by eliminating a portion of the drudgery associated with a lack of energy use. It also provides income-generating opportunities, raising owners' annual incomes by US$40 to US$100, and allows them to pursue other endeavors, such as education or other activities. The success of multifunctional platforms in Mali highlights the interdependency of all aspects of development and modern energy consumption. Women who own and manage a multifunctional platform machine have higher incomes, economic independence, more time for education, and ultimately a higher social status and a higher quality of life."**

Biomass Gasification for Shaft Power, Heat, and Electricity

Small modular gasification technology has important potential for farmers' cooperatives and collectives, with benefits for neighboring villages. The system uses a wide variety of biomass residues, such as coconut shells, coffee husks, wood wastes, and other woody biomass, to produce a high-quality gas that can provide heat, shaft horsepower, and electricity (see Figure 39). Available systems are in the range of 25 kWe to 75 kWe.

Figure 38 Biomass Gasification System



Source: Community Power Corporation, www.gocpc.com

In biomass gasification systems, biomass is broken down thermochemically by heat and oxygen to produce a synthesis gas that can be used to power internal combustion engines, boilers, furnaces, dryers, and chillers. Gasification technology is commercially available but currently expensive and mainly applicable to agricultural and horticultural processes that generate significant quantities of biomass residues.

Chapter 7: Hypothetical System Case Studies and Sample Calculations

The tables below present low, basic, and intermediate technology scenarios for complete value chain out-fitting based on different background assumptions. The first table describes the energy sources for each scenario.

Table 22 Energy Sources Suitable for Technology Options

Categories	Commodities/Technologies	Energy Sources
Low tech (<5 kWh/day)	Field packing of leafy, stem, or fruit vegetables, root, tuber and bulb crops, fruits and berries	Electric grid; Solar power with battery back-up
Basic tech (5 to 25 kWh/day)	Packinghouse operations and pre-cooling for tropical and subtropical fruits and vegetables; Evaporative cool storage. (Temperature range 15°C to 20°C)	Solar water heater, Electric grid; Generator (diesel or gas); Hybrid PV/ Generator systems with battery back-up
Intermediate tech (25 to 100 kWh/day)	Cooling and cold storage for temperate fruits and vegetables. (Temperature range 0°C to 7°C)	Electric grid; Generator (diesel or gas)
Modern tech (> 100 kWh/day)	Automated packinghouse operations, pre-cooling and cold storage for any kind of fruits and vegetables. (Temperature range down to 0°C)	Electric grid; diesel back-up generators

Source: Winrock International

Table 23 Case 1: Low Technology (< 3 kWh/day) < 1 MT/day

Action	Method	No. of Power-using Tools/ Equipment	Capital Cost	Energy Use	Hours of Use/Day	kWh/Day	Cost per kWh	Cost of Energy per Day
Harvest	Manual	0		0			0	0
Cleaning/ trimming	Manual, outdoors	0		0			0	0
Sorting/ grading	Manual	0		0			0	0
Packing	Manual, field packing	0		0			0	0
Pre-cooling	Via shade	0	$200	0			0	0
Cool storage	Night air ventilation (electric fan)	1	$300	0.1 kW	12	1.2 kWh	$0.35	$0.42
Transport	Animal-powered wagon	0		0			0	0
Total								$0.42

Source: Winrock International

Table 24 Case 2: Basic Technology (5 to 25 kWh / day) 1 to 2 MT / day

Action	Method	No. of Power-Using Tools/ Equipment	Capital Cost	Energy Use kW or L of Fuel/Hour	Hours of Use/ Day	kW hours /Day or L/Day	Cost per kWh or L	Cost of Energy per Day
Harvest	Manual	0		0			0	0
Cleaning/ trimming	Manual	0		0			0	0
Pest mgmt	Hot water dip	1	$500	18 to 30 kW	8	144 to 240 kWh	$0.35	$50 to $84
Cooling after hot water treatment	Ice bath	1	$6,000 to $10,000	varies	varies	27 to 67 kWh /MT	$0.35	$12 to $24
Sorting/ grading	Manual, natural lighting	0					0	0
Packing	Manual	0					0	0
Pre-cooling	Via evaporative forced air	2	$800	0.7 kWh/MT/ hr	12	8.4 kWh	$0.35	$2.94
Cool storage	Night air ventilation (electric fan)	1	$300	0.1	12	1.2	$0.35	$0.42
Transport	0.5 MT Porta-cooler	1	$1,600	2 kW	8	16 kWh	$0.35	$5.60
Total								$70 to $117

Source: Winrock International

Table 25 Case 3: Intermediate Technology (250 to 1,000 kWh / day) 3 to 5 MT / day

Action	Method	No. of Power-Using Tools/ Equipment	Capital Cost	Energy Use kW or L of Fuel/Hr	Hours of Use/Day	kW Hours /Day or L/ Day	Cost per kWh or L	Cost of Energy per Day/ MT
Harvest	Manual	0		0		0		
Water storage tower	Pump	1	varies	varies, 1.1 to 1.8 kW/Hr	8 hours/day	8.8 to 14.4 kWh/day	$0.35	$3.08 to $5.04
Cleaning/ drying	Spray washer, air dryer	1	$1,000	300 watts to 1.5 kW	8 hours/day	2.4 to 12 kWh/day	$0.35	$0.84 to $4.2
Pest management	Hot water dip	1	$500	36 to 60 kW	4	144 to 240 kWh	$0.35	$50 to $84
Cooling after hot water treatment	Ice bath				varies	27 to 67 kWh /MT	$0.35	$28.35 to $117
Sorting/ grading	Manual, high quality lighting	3	$50	1 kW	8	8 kWh	$0.35	$2.80
Packing	Manual	0		0				
Pre-cooling	Via portable forced air	2	$2,400	55 kWh / MT	8	165 to 275 kWh	$0.35	$58 to $96
Cold storage* (10 MT)	Cold room (refrigerated)	1	$30k	1.25 to 2.1 kWh /MT	24	300 to 500 kWh	$0.35	$105 to $175
Transport	20 ft reefer truck	1	lease					varies
Back-up generator	400 kW	1	$60- $80K	84 L/hour	varies			varies
Total								$197 to $396

* Cold storage cost is approximately $0.01 per kg per day

Source: Winrock International

Sample Calculations

The blank tables below can be used as a matrix to facilitate estimation of total combined power generation requirements and daily energy requirements for your facilities. The total power is not necessarily the peak power that you will require unless all applications are running at the same time. The end use equipment shown in the first column is indicative; you should replace these categories with each of the energy consuming elements in your own operations.

Table 26 Estimating Energy Use in Your Own Horticultural Operations: ELECTRICITY

Device or Technology	A Quantity	B Power (watts)	C= AxB Total watts	D On-time (hours/ day)	E= CxD Watts / Day	F=E/1000 kWh/Day	Cost/ kWh	Total Cost/Day
Water pump								
Washer								
Conveyor								
Lighting								
Hot water dip								
FA cooling								
Cold storage								

Table 27 Estimating Energy Use in Your Own Horticultural Operations: FOSSIL FUELS

Device or Technology	A Quantity	B Fuel Use L/hr	C= AxB Total L/hr	D On-time (hours/day)	E= CxD L /Day	Cost/L	Total Cost/ Day
Irrigation pump							
Planting (tractor pass)							
Propane-heated air blower							
Transport to packinghouse							
Transport to cold storage							
Transport to market							

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Glossary

Air curtain – a row of heavy plastic strips hung across an entrance to a cooled storage space to reduce heat loss by up to 80%.

ART (Advanced Refrigeration Technologies) Evaporator Fan Controller – an automatic fan speed regulator in a cool storage space that reduces energy usage by coordinating fan speed with inside/outside temperature differential and coolant flow in the refrigeration unit.

Batch hydro-cooler – a space in which packed produce (i.e., a pallet of crates) is subjected to a shower of cold water from above in order to lower the temperature through conduction.

Biodiesel – A liquid fuel made from processing of vegetable oil in a process called "esterification." Biodiesel is compatible with petroleum diesel and can be used in most diesel engines.

Blanching – quick and superficial steam or boiling water heating of fresh produce before freezing to maintain texture and color.

Centrifugal pump – a submersible pump in which turbines revolve around a central axis, effectively throwing water upward within a pipe.

Cooling tunnel – a space through which forced air is passed to reduce produce temperature; the space may be constructed using crates or pallets of produce themselves.

Curing – allowing harvested crops to dry and any harvest wounds to heal naturally before further packing or processing.

Desert cooler – an evaporative cooler, utilizing a storage space where air is blown through wet, porous materials on one end of the structure to cool the interior.

Dip – a bath of hot water, dilute chemical, or other liquid through which produce is passed for the purposes of disease management and reduced spoilage.

Drawdown – in a well, the additional vertical distance that water must be raised due to local depression of the water table caused by pumping.

Drip irrigation – a network of plastic pipes and perforated tapes through which water, and sometimes fertilizers, is delivered at a slow, measured rate directly to crop plants, thereby economizing water, improving sub-soil percolation, and diminishing weed growth.

Dynamic head – the total energy needed to raise water, i.e. the static head (vertical distance) plus discharge resistance (water table depression caused by pumping) and friction losses; expressed in meters.

Evaporative cooling – the application of water that, as it evaporates, lowers the temperature of produce or of a space in which produce is stored.

Fertigation – the addition of soluble fertilizers to water reservoirs in drip irrigation systems, in order to deliver fertilizers during the irrigation process.

Field curing – leaving harvested commodities in windrows or piles in the field (covered to protect them from direct sun) to allow bulb crops to dry before handing or storage, and for root and tuber crops to undergo natural healing of harvest wounds (suberization).

Flood irrigation – periodic, temporary inundation of cultivated areas.

Genset – a generator set, an electrical generator such as a solar panel or gasoline-powered generator located in proximity to the end-user rather than in a central location such as those utilized by commercial power providers.

Grid electric power – electricity which is supplied by a centralized utility rather than a small, stand-alone source.

Heat-assisted batch dryer – a space in which hot air passes over produce to dehydrate it to reduce spoilage and improve texture (typically used for nuts or dried fruit).

Highway van – a 20-foot or 40-foot metal sea freight container or truck trailer.

Immersion hydro-cooler – a tank in which produce is submerged in moving chilled water to lower its temperature and improve conservation.

Indirect solar drying – the use of a sun-heated space to dry produce without direct sun exposure.

Integral solar collector storage – the use of solar thermal collectors to heat and store water in a tank for warm temperature (<50°C) operations.

Outsulation – insulation materials and a reflective surface on the outside of a storage space to improve its thermal inertia.

Porta-cooler – an insulated box fitted with air conditioner and diesel generator on a traditional vehicle (pick-up truck, flatbed trailer).

Pre-cooling – the use of cold water or cold moving air to quickly reduce produce temperature immediately following harvest and prior to processing, packing, or cold storage.

Pressure pumping – the raising of water through the use of centrifugal or reciprocating pumps mounted below the water surface that push the water upward; pressure pumping is not subject to any natural head limit like suction pumping, but energy requirements vary in proportion to volume and dynamic head.

PV – photovoltaic, as in solar collector panels that convert solar radiation into electricity.

Radiant cooling – the use of reverse solar thermal collectors or reverse solar water heaters, to cool produce storage spaces.

Reciprocating pump – a pump that uses the back-and-forth motion of one or more pistons to move water.

Reefer – a truck with a diesel-powered refrigeration system for its cargo hold.

Resistance heating – heating using electric resistance elements (i.e., coils).

Rope-and-washer pump – a pump consisting of a loop of rope with rings at regular intervals and operated by means of a manual crank or a motor at the upper end. The rings on the rope pass into a pipe whose lower end is submerged, pushing water upward through the pipe as the rope loop revolves. The water emerges from the pipe's upper end, spilling into a chute for channeling into a canal or other receptacle.

Solar chiller – a small refrigeration unit that uses solar photovoltaic energy. Developed for storage of medicines, these units may not be cost-effective for produce because of their small size.

Solar photovoltaic collector – a panel designed to maximize the intake and capture of solar radiation by photovoltaic panels that convert this radiation into electrical energy.

Solar thermal collector – a panel designed to maximize the intake and capture of solar radiation, which heats water in pipes that pass through the panel for use in post-harvest crop processing or other uses.

Static head – the total vertical distance over which water is raised (below and above ground level).

Submersible pump – an electric or diesel water pump mounted below the water level in a well. Centrifugal action is used to raise water to the ground level or above.

Suction pumping – the moving of water using reciprocating pistons above a water source. Suction pumping has an absolute dynamic head limit of 9.8 meters, which usually translates to a practical static head limit of 7 to 8 meters.

Swamp cooler – see desert cooler.

Treadle pump – a water pump operated by foot pedals.

Waxing – the application of a thin protective coat of edible wax to produce to retain moisture and retard spoilage.

Well screen – a filter around a well tube that permits water entry while excluding solid particles.

Wind mechanical energy – work performed using the movement of a windmill directly, rather than converting it first to electrical energy.

Zero-energy cool chamber – a storage space constructed of wet sand between a double wall of brick, which reduces temperatures through evaporation without external energy inputs.

Conversion Factors

1 hp = 0.75 kW

1 therm = 29.3kWh = 100,000Btu = 105.5MJ

Natural gas = 39MJ/m3 = 10.83 kWh/m3

LPG propane (liquid) = 25.3MJ/L = 7kWh/L

1 MJ = 0.28 kWh (1 joule = 1 watt during 1 second)

1 ton of refrigeration = 3.5 kW = 12,000 BTU/hour (1 kWh = 3,412 BTU)

Gasoline = 34.7 MJ/L = 9.7 kWh/L

Diesel fuel = 39.8 MJ/L = 11.1 kWh/L

Temperature in degrees Celcius (Tc) = (5/9)*(Tf-32)

Temperature in degrees Fahrenheit (Tf) = (9/5)*(Tc+32)

For More Information

Listed below are additional resources for a more technical, in-depth understanding of electrification options:

1. National Renewable Energy Laboratory: www.nrel.gov
2. Sandia National Laboratories: http://www.sandia.gov/Renewable_Energy/renewable.htm
3. US Department of Energy, Energy Efficiency and Renewable Energy: http://www.eere.energy.gov/