ROCKY MOUNTAIN INSTITUTE®

Banana Farm 1.0

Factor Ten Engineering
Case Study

August 2010

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1. INTRODUCTION

Amory Lovins co-founded Rocky Mountain Institute in 1982 with a mission to enhance global prosperity and security by fostering the efficient use of resources. To demonstrate those principles, Mr. Lovins designed and helped build a structure that, when completed in 1984, became not only his home, but also RMI's headquarters and main workplace, and a showcase for RMI's green engineering practices.

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Mr. Lovins's design includes an indoor growing space that produces a year-round harvest of fruits, vegetables, herbs, and flowers. This is no small feat, given that the residence sits at an elevation of 7,100 feet in Snowmass, Colorado, where winter temperatures can fall as low as –47˚F and summertime highs can exceed 90˚F.

In a location facing such a wide range of conditions, achieving a comfortable indoor environment would normally require a major investment in energy-intensive systems to heat, ventilate, and air condition the space. Mr. Lovins's design avoids such so-called HVAC systems (except heat-recovery ventilation) by relying on a variety of passive features and integrated elements that we'll explain in the pages that follow. His design provides the same comfort, fresh air, and health as a conventional approach, but uses a small fraction of the energy.

What's more, by avoiding the purchase of costly HVAC systems upfront, Mr. Lovins was able to redirect the savings into efficient appliances that further cut the home's energy use and operating costs. The design is so thermally effective that Mr. Lovins can grow semi-tropical fruits indoors all year, at 1% of the heating cost of a comparable conventional home. The banana trees in the building's atrium—which produce numerous crops each year (#34 was just harvested)—have inspired a nickname for the home: the Banana Farm.

Living in this high-tech home is surprisingly simple. In deepest winter, on days approaching zero outside, the Lovinses need not fire up a furnace (there isn't one), as heat gained from the sun during the day is enough to warm the superinsulated residence. On hot summer days, the Lovinses manage their comfort by opening different windows at different times. Some windows are opened at night to cool the mass of the home. For ventilation during hot days, other windows are opened to allow warm air to rise and escape.

In 2006, 22 years after it was built, the Lovinses' home entered its second era. After years of incremental upgrades, the building received a major renovation. Changes included the installation of more and better solar panels for both heat and electricity, upgraded appliances, and other cutting-edge technologies. Mr. Lovins re-named his upgraded home Banana Farm 2.0. The original design, as it functioned from 1984 to 2006, is now known as Banana Farm 1.0. In this case study, all cost and energy analyses compare Banana Farm 1.0 to a conventional home of the same vintage. But before we explore the design process used for the Lovins residence, let's take a look at how a typical house is built.

10xE[1] results:	**10xE principles:**
• Save 99% of space heating • Save 90% of electricity • Save over half of fresh water • Save $10,254/year at 1983 prices • Half-year payback • Semi-tropical environment in a cold climate	• Define the end-use • Start with a clean sheet • Seek radical simplicity • Tunnel through the cost barrier • Wring multiple benefits from single expenditures

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[1] 10xE (Factor Ten Engineering) provides engineers with practical tools to achieve radical resource efficiency through integrative design, thereby saving their clients' money and helping solve some of the planet's most critical energy and climate problems. See Appendix A and www.10xE.org.

2. THE BASE CASE DESIGN FLOW

2.1. Overall design

To build most custom homes, an architect is hired to design and plan construction. To execute the construction, the architect, in turn, partners with a general contractor, with whom they have typically built many homes in the past. The bulk of the architect's design work and budget analysis is spent on visible design details, which, as a rule, attract the greatest interest from homeowners. These include the building's exterior appearance, views to the outside, materials and finishes, color schemes indoors and out, and landscaping, to name a few.

Architects strive to design buildings that provide adequate services, such as light, heat, and cooling. But few pay attention to making the home energy- and resource-efficient. Design occurs in a series of decisions that are often disconnected from one to the next. For example, the building form is produced, and then electrical and mechanical equipment is specified to create thermally and visually comfortable spaces. The building form and orientation are often chosen without concern for how the lighting and especially the mechanical equipment will be affected: a preponderance of south-facing windows, for instance, will bring in more natural light and solar heat, cutting the need for both electric lights and furnace heating.

On a conventional project, in the inevitable event that there's a need to cut costs, decisions are often made to cut near-term construction costs first. For example, higher-cost materials such as thick masonry walls may be downgraded to a thinner wood-frame structure. But rarely are these decisions taken with any sense of how they will increase long-term energy use and drive up operating costs. Often, near-term savings lead to a less energy-efficient home and higher long-term costs.

In rare instances, a feature is made more efficient than building codes require. Yet here, too, each component is evaluated in isolation with little assessment of its impact on other systems. For instance, an engineer may be hired to calculate the energy saved if the roof insulation is increased. If the direct payback is reasonable for the owner, then the added insulation is likely to be installed. Yet it's unlikely that the engineer will capture second-order savings, such as reducing the capacity of the furnace and air-conditioner.

2.2. Engineering

After the architect produces a conceptual design for the house, the general contractor will typically provide the details of four main systems: the structure, HVAC, plumbing, and electrical. Usually these systems, vital to the operation of a building, are considered and installed with a minimum of site-specific analysis.

Contractors generally base their work on previous projects, using rules of thumb and local building codes. What's more, the compensation architects and contractors receive is often a percentage of the cost of building materials and labor that they specify. This creates a perverse incentive to design and install systems that are larger, more costly, and more energy-consuming than necessary.

There are still other disincentives to designing for efficiency. A major concern of the contractor is to avoid being called back to address problems with construction, as can happen when systems are under-sized. Thus, architects and contractors will consistently err on the side of oversized, less efficient HVAC equipment. Operating costs and energy efficiency then suffer even though the building complies with all construction and safety codes.

2.3. Making the home functional

In conventional construction, the owners outfit their houses with a variety of devices to enhance comfort and convenience. These include lamps, humidifiers, dehumidifiers, washing machines, dryers, stereos, and other appliances. Also, they may invest in aesthetic upgrades to floor coverings, window treatments, and interior wall finishes. These are all areas where consumers can face challenges making the best long-term choices. In the interest of saving on the purchase price of an appliance, for instance, a consumer may opt for a less-efficient unit, thereby locking in much higher long-term costs for the energy those devices will consume.

3. 10XE CASE

It's not difficult to escape the efficiency and cost traps described above. To build the Banana Farm, Mr. Lovins took a different route. First, he focused not on the size, scale, or style of the home he desired. Rather he envisioned the services he needed it to deliver. Function, he found, would help define form.

His priorities included overall comfort during all seasons, a working environment that stimulated productivity, a semi-tropical indoor ecosystem, enhanced aesthetic elements, and good acoustic performance. He wanted a nice home, certainly, but he also wanted its operation to use as little energy as possible, at least without resorting to ultra-expensive materials or exotic technologies. To achieve these goals, Mr. Lovins started exploring how the entire design of his home could help fulfill these goals.

Mr. Lovins knew it would be a challenge to achieve the desired thermal comfort in the house because of Snowmass's warm summers and very cold winters. Instead of simply installing a few oversized furnaces, he decided to combine super-efficient with passive-solar thermal design.

The building's shape, walls, roof, insulation, mechanical and electrical systems, tight construction, and windows were designed in coordination, allowing the house to be warm in winter and cool in summer, yet avoiding the cost and complexity of a traditional HVAC system. In this process, experts in a variety of disciplines—including structural, thermal, soil, water, and electrical—designed their systems together.

To minimize heat loss in the winter, Mr. Lovins designed the house with superinsulation and a variety of systems that recover, rather than lose, heat. To store solar warmth, the home relies on superwindows that lose very little heat and face south so they receive the sun's heat throughout the day. This energy is absorbed in thick walls designed to release the heat slowly back into the home at night, as indoor temperatures cool. In conventional home construction, superwindows and superinsulation are rarely used because of the belief that they won't save enough energy to justify their extra cost. Mr. Lovins's house disproved this convention since the extra insulation he selected eliminated the need for an expensive furnace and associated ductwork: he optimized insulation investment against saved operating plus capital costs.

Mr. Lovins then installed additional energy-saving devices, again starting from the end-use perspective. Installing efficient showerheads and faucets reduced the amount of hot water needed in the home, which in turn helped decrease the size of the solar water heaters. Efficient lighting, daylighting, an advanced washing machine, and other appliances all increase the home's energy savings.

10XE PRINCIPLE

Define the end-use

Lovins based his design on what he wanted a home to do.

10XE PRINCIPLE

Start with a clean sheet

Lovins did not restrict his design to what had been done before.

Many of the energy-saving tricks required advanced planning to achieve the greatest efficiency and economic gains. For example, the Lovinses also installed a passive-solar clothes-drying closet: dark colored walls absorb sunlight, warming up the air; overhead clothing racks can be raised and lowered.

3.1. Insulation system, thermal mass, and passive solar gains

To maintain comfort without a traditional heating system, the house was built to be airtight and is super-insulated to about twice normal levels. The house's massive walls and thick concrete floor capture solar energy as heat. The captured heat slowly radiates throughout the house over the course of hours, days, weeks, and months. A doubled area of superwindows facing in various directions, nearly all more or less south, helps the home harvest heat from the sun. Here we'll explore some of the most unusual features in detail.

3.1.1 Building structure

Curved walls. While unconventional and often costlier, curved walls are stronger, look nicer, and have greater functionality. They help capture and deliver heat and light from various directions. Acoustics benefit as well, since the slightly asymmetric curves minimize echoes. Curved walls resisted twisting while concrete was being placed in movable wooden forms to create the walls, a process known as slipforming, thus saving materials for the same torsional strength.

The walls can also create surprising experiences. From several positions in the house, the non-linear shapes make it possible to see outside while simultaneously

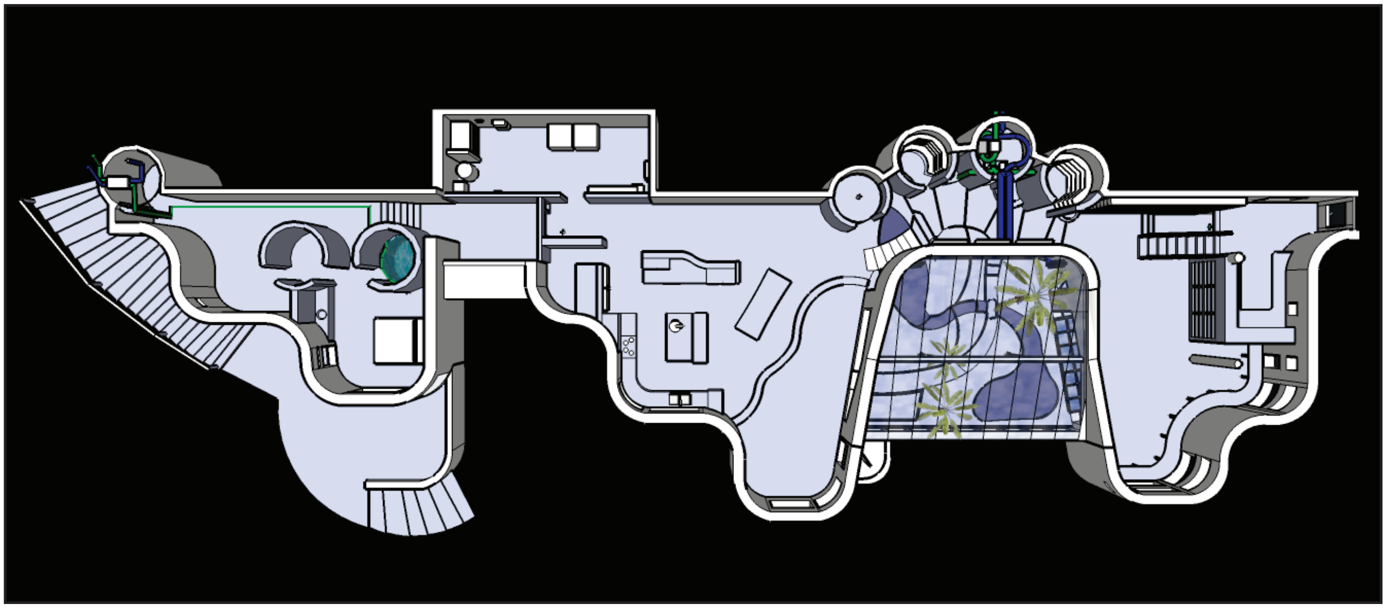

Figure 1. Plan view

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10xE PRINCIPLE

Wring multiple benefits from single expenditures

Curved walls improve overall building performance in five main ways. They enhance acoustics, improve aesthetics, strengthen structure, reduce outside air turbulence, and improve solar heat and light delivery.

peering across into other parts of the building, and they make the thick, recurving walls look even more solid because one can often view their inside and outside surfaces simultaneously.

There are exterior benefits, too. The smooth exterior shape cuts down wind turbulence, reducing both wind noise and heat loss. Massing the building's taller structures on its west end tends to produce a wind eddy that helps keep the front walkway clear of snow during northwesterly blizzards.

Wall components. The building's walls have shapes, openings, and thermal characteristics that are oriented to optimize their seasonal performance. Most windows, for example, face south to help the interior absorb the sun's warmth. Heat is also stored in the central arch, the earth in the atrium's greenhouse (see section 3.1.3), the inner walls, the floor slab, and the soil beneath it. Variations in the heat-absorbing and reradiating qualities of these materials mean heat migrates through the structure slowly, in complex flows, on times-scales ranging from hours to months. Some of the heat one may feel when visiting the building in November may have been absorbed in July. Lags between air temperature and mean radiant temperature help smooth their average, which produces one's sensation of thermal comfort. The steel-reinforced, slipformed walls are 16 inches thick, and consist of two six-inch courses of high-strength masonry sandwiching four inches of polyurethane foam, with an insulation value of R-33[2].

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[2] Heat flow is measured (in American units) as BTU/hour per sq ft of area per F° of temperature difference. Insulating value (R) is one divided by heat flow. An R-20 wall resists heat flow twice as well as an R-10 wall. Double-paned windows offer a scant R-2 worth of insulation. A foot of glass fiber insulation, typical in some attics, is about R-38. Lovins used the best polyurethane foam available at the time, with a certified value of R-8.3 per square inch because it was blown with CFCs. Since CFC-free foam wasn't yet available, he worked with the manufacturer and on construction details to minimize potential CFC leakage during and after construction. Today's CFC-free foams have lower insulating values.

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Enhanced by heat stored during the day in the outer masonry, the foam effectively insulates around R-40, roughly twice what's normally considered cost-effective. On the interior, the thermal mass of the inner course of masonry stores heat that transfers slowly into the living space. The house also has an extra-deep insulating skirt around its foundation, to reduce the seepage of heat into the earth while capturing far more thermal mass beneath the slab, which was poured on grade. The back of the house is earth-sheltered, so only the superinsulated northeast corner of the north wall sticks up above the ground. The cantilevered arch at the back of the garden in the Lovins home provides a host of services. Built with 16 tons of concrete and 1.5 tons of reinforcing steel in 13 groups, the arch's dozen functions include controlling and storing heat; aesthetics and acoustics; diffusing light; holding up the roof beams and glazing; distributing various cantilevered loads; housing the cooling vents and atrium lights; and actively collecting solar heat. In addition, the arch forms a white "light scoop," bouncing daylight into the sides of the building and helping to make the whole structure up to 95% daylit.

3.1.2 Superwindows

Much of the building's performance is due to its advanced windows. Many off-the-shelf windows couldn't meet project requirements, but some commercially produced, high-performance windows can be costly since they are produced on a small scale. To produce the original R-5.3-center-of-glass windows economically, the design team worked closely with Alpen Glass, now a unit of Serious Materials. Gradually retrofitting this firm's successive generations of glazings had by 2005 raised that R-value to 12.5.

10xE Principle

Wring multiple benefits from single expenditures

The atrium's arch delivers a dozen benefits, but only has to be paid for once.

The advanced windows installed at the Banana Farm more than doubled originally, and later more than tripled, the performance of standard "low-e" (low emissivity) glazings. The original glazings were argon filled and used one spectrally selective surface. Later many were given a second selective surface and filled with krypton, which insulates twice as well as air. Today, all the windows have four selective surfaces (two on each side of two suspended polyester films) and xenon fill. This design, 1.39 inches thick, loses only 8% as much heat as a single pane of glass, but lets in 52% of visible light and 41% of the total solar energy. Three special R-20 units now include low-e glass too, insulating like 20+ sheets of glass while admitting 41% of light and 35% of total solar energy.

Heat loss from around the edge of the windowpane, where it attaches to the frame, is a major villain in window performance. Since the various elements of a multi-pane unit must be both mechanically separated and hermetically sealed, aluminum has traditionally been used as a spacer. Yet aluminum leaks heat quickly. So in the Banana Farm's 1983 superwindows, aluminum spacers were replaced with steel, cutting conductivity by over 80%. In today's units, the interior glass-to-glass "thermal bridge" was replaced with better polyester spacers, and many sashes are fiberglass stuffed with superinsulating nanogel.

3.1.3 Atrium

The heart of the Lovinses' home is a vaulted central atrium that spreads warmth and light throughout the core of the building. Naturally, it also houses Mr. Lovins's Banana Farm, a 900-sq.-ft. garden teeming with tropical plants and fishponds. The atrium collects solar energy in five ways: photosynthesis; visible light; hot air (to maximize ventilation heat recovery, which also

10xE Principle

Seek radical simplicity

Many homeowners would first consider Energy Star appliances to achieve efficiency. But starting with passive design enables even bigger savings.

recovers distilled-water condensate for irrigation without salting the soil from the very hard local water); hot water (preheating incoming water to be actively solar-heated later); and heat captured in the soil and water.

On hot days, excess heat is released from high vents. On the hottest days, vertical windows on the south side of the atrium can be opened to create a "stack effect" so hot air is sucked out the vents, chimney-like.

The arch's sides are shaped to let the low winter sun penetrate all the way back to the atrium's north wall, while the high-angle summer sun is confined within the arch for easy cooling out the vents above. This geometry automatically helps keep the north side of the atrium sufficiently warm and bright in winter without making it hot and glary in summer, and helps even out the distribution of heat and light through the atrium and the adjacent spaces.

3.2. Passive solar appliances

3.2.1 Passive hot water

Conventional homes take chilly, fresh water straight from public water mains and then heat it using oil, gas, or electricity. The Lovinses' home instead uses a combination of heat sources from the house to pre-warm the water, before using active solar energy to heat it further.

Incoming water enters the house at around 35–55˚F. The first stop is the greenhouse, where the water circulates through pipes in the arch's south-facing back wall, rising to or often well above room temperature. From there, the preheated water flows through a coil in the top of a heavily insulated tank whose 1,500-gallon fixed inventory of water stores heat added by a water-antifreeze mixture circulating through a coil in the bottom of the tank and delivering heat from active solar panels on the roof. Sinking to the bottom of the tank, the coldest water makes the solar panels work more efficiently. Rising to the top of the tank, the hottest water surrounds the water-heating coil. This stratification automatically maximizes solar effciency.

© Judy Hill Lovins

10xE Principle

Define the end-use

The Lovinses' solar drying closet may take longer to dry clothes than a conventional dryer, but it can handle more clothes in a single batch—a feature many consumers would welcome. Yet conventional building technologies rarely offer it.

Water heated by passive and active solar energy then flows directly to the efficient showerhead or faucet. If, as rarely happens, the storage tank cannot heat the water sufficiently after prolonged winter cloudiness, which once lasted 39 days, a backup propane tankless heater (later eliminated in Banana Farm 2.0) kicks in to add just enough heat to reach the desired temperature, adding about 1% of the annual water heating.

3.2.2 Passive clothes-dryer

To dry laundry, the Lovinses' home relies on a passive dryer, which uses passively solar-heated hot air. The dryer is a dedicated closet, heated via sunlight that enters through a south-facing superwindow. Dark-colored walls absorb heat; a small fan circulates air downwards; a small air-to-air heat exchanger recovers heat from moist exhaust air and transfers it to cold, dry, fresh incoming air; and a boat winch easily raises and lowers a "vertical clothesline" loaded with damp clothes. (Improvements in Banana Farm 2.0 eliminated the fan and idled the heat exchanger while capturing most of the heat from nearby monitoring equipment.)

3.3. Energy-efficient and water-saving appliances

3.3.1 Refrigerator

The Lovinses' refrigerator, with 16 cubic feet of capacity, looks and works like a regular fridge. But it relies on a variety of hidden innovations to dramatically cut its energy use. First, it's surrounded by far more insulation than a conventional design, so once the inside is cool, it stays cool for longer. The refrigerator's heat-producing components are above, not below, the food compartment, so heat from the compressor and condenser rises away from the fridge into the room, where it's usually wanted.

The fridge's most surprising feature is a shaded "cooling fin" that's mounted on the outside of the building, and attaches to the fridge via a well-insulated tube. Warm refrigerant gas rises into the fin, releasing waste heat into the ambient air. When that outside air is cold enough, the gas condenses back to liquid, which gravity draws back down into the fridge to do more cooling. Using outdoor air via this "heat pipe" lets the compressor stay off during the colder half of the year, saving about half the electricity.

Working together, these features mean the fridge uses just 85 kWh of electricity per year, just 8% of the consumption of a conventional fridge of the same vintage, and saving each year about enough coal at the power plant to fill the inside of the fridge. The freezer lacks such a cooling fin, but still needs just 13% of normal energy used by units sold in the early 1980s (today's are better).

3.3.2 Water and wastewater

To reuse water, the Banana Farm handles waste streams differently. Blackwater from toilets, tainted with sewage or other heavy waste, is sent directly to the building's code-required sewage treatment system—a septic tank and leach field. But graywater, the lightly polluted water that goes down the drain from sinks and the washing machine and dishwasher, was plumbed separately. When Colorado codes eventually allow this, the graywater can ultimately be sand-filtered and then fed by gravity to irrigate the pastures near the house, extending their growing season by adding nutrients and warmth.

Advanced showerheads also help save water. The master bathroom originally used air-assisted showers, first invented by Buckminster Fuller for submarines, that use water sparingly—just 0.3 gallons per minute, a fifth of the rate of today's commercial "low flow" showerheads—while still providing comfortable pressure. These units are currently disused pending possible repairs.

Likewise, the sinks use faucet aerators, which spread a stream of water into many little droplets that wet better and create the feel of high water flow. To make it easier to avoid leaving the water running while performing tasks in the kitchen and bathroom, intelligent taps can be turned off and on instantly, with the touch of a fingertip and without losing the temperature setting.

The dishwasher and clothes-washer are among the most efficient models available. The dishwasher uses smart sensors to stop washing or rinsing once the water comes out clean. The clothes-washer combines smart controls with extra-high spin speed, since it takes far less energy to dry clothes using centrifugal force than by using heat.

3.3.3 Lighting

Various types of compact fluorescent lamps (CFLs) were installed for Banana Farm 1.0, and upgraded in subsequent years. CFLs use just a fifth or so of the electricity of conventional incandescent bulbs. Reflectors or other optical accessories direct or diffuse the light to further boost the amount of usable illumination produced by each bulb. In the kitchen, one of the first dimming electronic ballasts used a light sensor to measure the daylight coming in through the windows and dim the electric lighting accordingly, halving again the energy these lights consumed annually.

4. COMPARISON OF BASE CASE AND 10XE CASE

4.1 Process steps comparison

Base case design

1. Starts with the requirements from the owner and building codes. An architect or general contractor typically passes designs down to the next more specific level of engineer, who then does likewise to the next specialist.

2. Optimizes each component separately for energy efficiency, and only against saved energy, not saved equipment. Thus there are only operating costs savings, but no capital savings.

3. Makes decisions based on experience and rules of thumb. Most engineers and contractors estimate the size of the heating system based on the area of the house, surface area of windows, and other factors, disregarding the actual performance of the components or unique siting issues.

4. Considers household appliances after construction. Even if an owner has specific design requirements, they typically go no further than "leave space for a refrigerator."

5. Leads to a premature termination of investment in additional energy efficiency features. As costs for additional improvements rise, owners, architects and contractors deem their impact to be too small, and stop further efficiency efforts (see figure below).

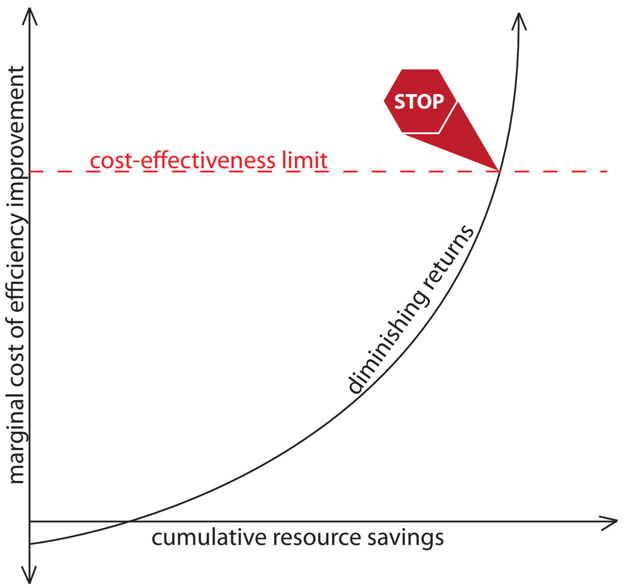
10xE design

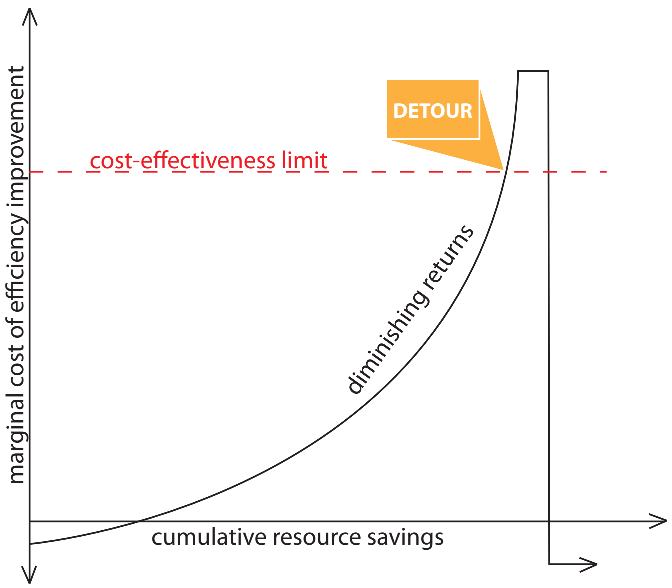
1. Starts by focusing on functional goals (e.g., "achieve satisfying thermal comfort," rather than "install a big enough heating system"). Emphasizes passive systems integrating (1) superinsulation, (2) thermal mass, and (3) passive solar gain.

2. Designs systems to achieve many benefits from a single expenditure: Superwindows, for example, can improve daylighting, summer and winter comfort, noise-blocking, and about nine other factors. Most components in the Lovinses' home serve at least three functions, many six or more.

3. Tunnels through the cost barrier. For instance, superinsulation adds cost, but if combined with other passive measures, the entire heating system—furnaces, ducts, fans, pipes, pumps, wires, controls, fuel-supply arrangements—can be eliminated, saving both up-front capital costs and long-run energy use (see figure below).

4. Rewards investment in multiple, incremental efficiency features with a sudden sharp decrease in overall construction costs and far lower long-term costs for energy and maintenance.





4.2 Quantitative cost and performance comparison

Here, we share some key comparisons of the remarkable cost advantages of Mr. Lovins's integrative design approach. A more detailed analysis of these savings is in the appendix.

Heat. A furnace was unnecessary thanks to the advanced system of insulation, heat recovery, passive heat gain, thick walls, and high-quality windows. Therefore, including the avoided capital costs of the furnace (including its heat distribution equipment and the troublesome wiring, fuel piping, and electric controls), the efficiency measures had a half-year payback against energy savings. The features that eliminated the conventional heating system cost roughly $1,056 less than it would have cost to buy and install (let alone operate), but resulted in a roughly 99% saving on space-heating energy.

Air conditioning. The radiant heat from the thermal mass and greenhouse also provided better comfort than a typical ventilation system. Because the atrium was designed not to overheat, and windows could be opened to pull in cool currents while venting warm air, a cooling system was also unnecessary. (However, overhead glass, even superwindows, is usually inadvisable for low-altitude sites: where the nights aren't always cool, vertical glazing shielded from summer sun by an overhang is generally safer.)

Other. These saved costs not only paid for the insulation, but also provided more capital for Mr. Lovins to invest in more energy-saving devices and systems. He reinvested another ~$6,000 to save about 99% of the water-heating energy, some 90% of the household electricity, and half the water, too.

Construction costs. Upon completion in 1984, total direct construction costs for the building (excluding land and finance), was about $130 per sq. ft. The price tag includes more than $50,000 worth of built-in furniture. It also counts at market value the cost of all volunteered labor and donated or discounted equipment.

Within the local housing market, the per-square-foot cost for this building was below the average for contemporary custom buildings of comparable quality at the time. In the early 1980s, building costs in the area were nearly twice the national average. All non-native materials had to be trucked in, skilled craft labor was costly, and the building season is short, with frost possible any day of the year.

Taken together, the investments in energy and water savings increased construction cost by just 1% net: about $4,944 or $1.28 per sq. ft.

Operating costs. The energy- and water-saving features in the Lovinses' home are among the most advanced in the world: the house uses no fossil-fuel heat, about a tenth the usual amount of electricity, and less than half the normal amount of water. Compared with normal local building practice and the lowest-cost conventional fuels in the region—firewood and propane—and using electricity from the grid, the building saves at least $10,254 in energy costs per year, or an average of $28 per day.

Return on investment. Overall, investments in energy savings paid for themselves in six months (at the time, Mr. Lovins estimated ten months) at 1984 energy prices, using 1983–84 technologies. One could do better today, even eliminating initial capital cost differences between an advanced home and a standard one, because since 1984, most of the technologies have become much better and cheaper.

5. CONCLUSION

5.1 Guiding 10xE principles and their implications

Principle 5. Define the end-use. Mr. Lovins started his design process by focusing on what he wanted the home to do.

Principle 10. Start with a clean sheet. Mr. Lovins did not restrict his design to what had been done before.

Principle 13. Seek radical simplicity. Conventional design would mandate a heating system in this severe climate. Mr. Lovins designed a house that harvests, holds, and distributes the warmth of the sun, thereby eliminating the conventional heating system.

Principle 14. Tunnel through the cost barrier. Extra investment in insulation and energy-saving appliances has always been a barrier for most designers and engineers. But as this case shows, when the incremental improvement reaches a critical level, some major capital costs, such as the furnace(s) and duct-work, can all be eliminated, generating enormous savings in capital costs as well as operating costs.

Principle 15. Wring multiple benefits from single expenditures. Throughout the Lovinses' home, most components serve many functions. For a full explanation of all 10xE principles, go to 10xE.org.

5.2 Banana Farm 2.0 and beyond

The process of improving and upgrading the Lovinses' home continues today. Guided by 10xE principles, the building went through a major renovation in 2006–09, leading to Banana Farm 2.0. Ongoing improvements ensure that the Lovinses' home continues to be a showcase of energy efficiency, attracting thousands of visitors every year and more than 100,000 so far.

Windows. Throughout the house, the windows' center-of-glass R-value reached an industry-leading level of 12.5—over twice the insulating value of the original 1983 windows, as described above. On a 0°F winter day, the glass inside these superwindows is 66°F, in contrast to 16°F for single glazing. The insulating value and airtightness of the operable sashes has also been greatly improved.

Solar. Starting in the 1980s, Mr. Lovins began installing photovoltaic (PV) panels to supply electricity to the house. One bank of panels used sensors and small servomotors to keep the panels pointed at the sun; this tracking ability boosted their output by up to 40%. Together with larger banks of non-tracking panels, the solar array grew to a peak capacity of 3.6 KW. A few years ago, a 6-kW Sunpower array was added, and new power electronics made the system more efficient and able to run with or without the grid. The meter now normally runs backwards, reducing coal power required for the grid. At night, the house runs entirely on purchased utility windpower—or, if the grid has failed, on stored daytime solar power.

Lighting. A fifth major lighting retrofit was undertaken in mid-2008. Most fluorescents were replaced with advanced light emitting diodes (LEDs) that give off warm, pleasing light, use more precise and efficient light distribution, and use only about half the energy of CFLs. In addition, the harsh luminance ratios in the front hallway (north of the kitchen) were relieved in early 2009 by retrofitting a daylight diffuser fed by horizontal light tubes from the clothes-drying clerestory in the utility room to the north (page 5, upper left photo).

Other. Mr. Lovins also installed two R-60 air-lock vacuum-panel doors, additional roof and north-wall insulation, energy- and water-saving bathroom fixtures with even better performance, restored airtightness, greatly improved air-to-air heat exchangers, a super-efficient electric cooktop integrated with special pots, and other improvements throughout.

A ~200-point data monitoring system has been added and is being commissioned in summer 2010. Data will then be posted to the Internet. Initial observations suggest that the monitoring system may be using more annual electricity than the lights and appliances.

For more information, photos, and a virtual tour of the Banana Farm, please visit: www.rmi.org/rmi/Amory's+Private+Residence.

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APPENDIX

Appendix A: Factor Ten Engineering

Factor Ten Engineering (10xE) is an ambitious initiative undertaken by Rocky Mountain Institute (RMI) to strengthen design and engineering pedagogy and practice. Though a tenfold gain in resource productivity is achievable, it is not for the faint-hearted. It requires bold and gutsy designers willing to question familiar practice and work closely with people from other disciplines.

From the radically efficient design RMI regularly creates and teaches, we have become convinced that *radical*[1] efficiency by design (a) works, (b) can be adopted by designers new to it, (c) can be formally taught, (d) can yield extraordinary value, often including big savings that cost less than small savings and important synergies with renewable and distributed supply, and (e) should spread rapidly if we and others develop the right examples (proofs), principles, and tools (notably design software), and properly inform design customers/users and improve reward systems.

"FACTOR TEN" IS AN ASPIRATIONAL GOAL OF ROUGHLY TENFOLD HIGHER RESOURCE PRODUCTIVITY.

In light of this need, 10xE is an RMI initiative focused on transforming the teaching and practice of engineering and design, in order to spread *radical* and *cost-competitive* energy and resource efficiency. Based on many collaborations with practicing engineers and designers, we believe that the following actions must happen to enable this transformation:

At the academic level:

- Provide case studies and design principles that explain how to do integrative design and illustrate its major benefits
- Recruit professors and universities to teach the cases and principles
- Encourage students to learn them

At the industry level:

- Convince project decision-makers that greater attention to energy and resource use is indispensable
- Provide hands-on experiences to show concretely what is different and why it is better
- Provide case studies and design principles that explain how to do integrative design and illustrate its major benefits
- Create the tools and reward systems that will enable implementation

Find more about Factor Ten Engineering, whole-system thinking, and 10xE principles at 10xE.org. Explore RMI's experience redesigning buildings, transportation and energy systems at RMI.org.

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[1] Typically 5–10 fold

Appendix B: Technical analysis

B.1 Cost analysis

To assess the cost reductions of Mr. Lovins's super-efficient home built in 1982–84, we compare it here to a base case: the cost to build a similarly sized and shaped masonry house that meets local (Pitkin County, Colorado) 1982 code for insulation and is heated and cooled by a standard HVAC system. All money values here are in 1983 U.S. dollars.

Here are the minimum insulation codes that the base case house is required to meet:

- Exterior above-grade walls, R-20
- Exterior roof, R-30 (if lower than 12 ft.) or R-40 (if higher than 12 ft.)
- Interior floor above cold space, R-19
- Perimeter below-grade walls, R-13
- Perimeter cold crawl space, R-13
- Unheated slab perimeter on-grade, R-10 to 3.5 ft. below grade
- Heated slab perimeter on-grade, R-13 to 3.5 ft. below grade
- We assume values for south windows, non-south windows, sky-facing windows, and doors at R-1.7

From the information above and prices provided by original engineers in the project in 1984, we calculated the cost premiums of different components:

Table 1. Cost analysis

Parts to compare	**10xE case method**	**Base case method**	**Cost premium**
AAHX costs, large	2 units	Not used	3,144
AAHX costs, small	3 units	Not used	483
Initial super windows	Heat mirror, R-5.3	Clear double paned, R-1.7	5,600
Ceiling and roofing insulation	7 in. polyurethane, R-60	3.35 in. polyurethane, R-30	4,059
Wall insulation	4 in. polyurethane, R-40-effective	2.4 in. polyurethane, R-13	3,713
Insulation skirt around footers	4-in. thick, 6 ft. deep styrofoam	3-in. thick, 3.5-deep styrofoam	2,114
			Cost premium, total: $19,112

B.2 Saving analysis

B.2.1 Capital savings

To estimate the cost of the furnace system in the base case, we need first to size the furnace. This sizing calculation is rarely used in real-world scenarios, because normally contractors just decide based on past experience.

Equation 1. Furnace sizing

Parts to compare	10xE case method	Base case method	Cost premium, $
Furnace	None	2.5*150MBTU/h furnaces, plus 15 ft^2 of furnace floorspace valued at \$125/ft^2	(5,168)*
Ducts	None	500 feet of ducts for furnaces above, and 20% more on the labor cost (the house's geometry and structure make the ducts very hard to fit in)	(15,000) *
		(Savings) Total:	(20,168)
		Net cost premium for construction:	(1,056)

$$Q = (U \times A \text{ in total}) \times (T_{set} - T_{design}) \times (\text{Pickup factor}) \div (\text{efficiency of distribution})$$

Q: size of the furnace
U: ratio of the temperature difference across an insulator and the heat flow per unit area. U=1/R.
A: areas of insulators such as walls and windows
Tset: the air temperature we want to maintain in the house, here assumed to be 65ºF
Tdesign: the lowest outdoor temperature in the climate, here assumed to be –40ºF (which then occurred during a few nights in most winters)
Pickup factor: Heating systems must be sized for a significant "piping and pickup" factor which accounts for the extra "start-up" heat needed to heat the heavy network of pipes and terminal devices.
Efficiency of distribution: There is always heat loss in the heating system; the efficiency of distribution is the actual heat received divided by the total heat transferred from the source.
Assumptions. Infiltration rate of 0.75 air changes per hour (ach), assuming a volume of 50,000 cubic ft. for the house (a recent takeoff indicated 37,085, but the difference to performance is unimportant).

From the R-values required by code and our assumptions, we calculated the size of the furnace to be 341,959 BTU/hour. Thus, we calculated the capital cost of the heating system, which is also the savings from eliminating it:

Table 2. Saving analysis

Heating energy source	Furnace or stove efficiency	Price per MMBtu, $
Propane	60%	\$9.34
Firewood	40%	\$5.56

B.2.2 Energy savings

To know how much energy was saved on heating every year, we have the following equations for calculation:

Q fuel: actual consumed energy per year
Q delivered: energy to be delivered per year
HDD: Heating degree day are quantitative indices designed to reflect the demand for energy needed to heat a home or business. These indices are derived from daily temperature observations, and the heating requirements for a given structure at a specific location are considered to be directly proportional to the number of HDDs at that location.

We assumed that a normally designed comparable house would heat with 50% firewood and 50% propane, approximating the locally least-cost mix. These fuels have different heating efficiency values and 1984 prices as follows:

Table 3. Heating energy source

Based on the equations, house facts, and other assumptions above, the saved energy cost on space heating would be $5,864 per year. From the building's *Visitor's Guide* (1984), the electricity usage averaged 0.2 W per sq. ft. and it was only a tenth of the base case scenario. This led to electricity savings of $4,100 per year. We assumed an average of 4,479 kWh per year usage of water heating for the house.[3] We got to a saving of $290 per year. The total energy saving for the house is thus $10,254 per year.

B.2.3 Total payback calculation

Lastly, Mr. Lovins invested an additional $6,000 in the original solar-water-heating system and on more efficient electric appliances. The final payback calculated is about 6 months, given below.

Equation 4. Payback calculation

(–$1,056 net extra construction cost + $6,000 extra investment in solar hot water and electricity savings)
÷ $10,254 annual savings = **0.5 years**

This is in reasonable agreement with Mr. Lovins's published estimate of a ten-month payback at 1984 energy prices.

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[3] COMPETITEK, *The State of the Art: Water Heating*, Rocky Mountain Institute, October 1991 Edition.