Chapter 9
Conclusions and a look to the Future

Time changes everything except something within us which is always surprised by change.
Thomas Hardy

Opening Questions:

What is new in this study?
How are the findings significant?
Why were the findings so surprising?
What are the big implications of this study?
How might readers react to these conclusions?
How can public policy help incentivize the transition?
What research is needed to further develop these ideas?
How do I live sustainably after addressing housing/transport?
What might the future hold, either to change or amplify these ideas?

Data and Analysis:

Nearly all choices in the home building and equipping process have long-term implications, both because new installations have expected long life, and because most homeowners finance their investments over long periods of time. This long-term dimension requires the addition of cost of funds and inflation in financial analyses, and more complicated payback calculations, to portray reality; we have offered that detailed analysis in the preceding chapters. The aim in this final chapter is to bring all the big elements and arguments together, without the deep complexities, to clearly connect related elements into a comprehensive whole, while elucidating flow, relationships, implications and impact. Readers who have jumped over the details in previous chapters to this summary set of conclusions are invited to explore the data and analyses at the heart of this text; we have attempted to provide place references where relevant.

When our small team gathered to study sustainability issues in housing, and build what we expected would be the most environmentally-responsible home (for its size and climate), we found near consensus opinion in the industry; invest first in thermal envelope upgrades in order to reduce heat loss and energy use. Active solar is mentioned as a helpful addition, but often as an optional feature, or secondary priority if budgets permit. Passive solar is represented nearly as much as active systems in the literature, and a common assumption prevails that onsite PV solar requires a financial sacrifice. Further, very little attention has been given to the embodied energy of construction and equipment choices, and we found almost no studies addressing the trade-offs between embodied and operational energy by specific application, and especially across competing systems.

It was therefore surprising to us when data led us down very different paths to new discoveries, outcomes, and implications. The new findings clearly show that solar PV should be prioritized above all other construction or renovation issues to achieve an environmentally-sensitive home that is affordable to most. It is our strong opinion that active onsite solar should be considered and designed into every new building in the U.S. and added to existing buildings where possible and practical. This reflects clear outcomes on the direct and relative benefits of active solar on the individual merits of financial return, embodied and operational energy trade-offs, materials use, opportunity costs, and overall ecological impact. In nearly every region[1] of the country, the investment in solar PV will earn attractive rates of return, and in most places better returns than expected from U.S. equity markets, on average, over the expected life of the system.

The findings of this study implore a new priority. Rather than making choices and incurring expenses with the aim of reducing heat loss and energy use[2], the *first priority* should be to invest in onsite solar PV to harness the relentless[3] energy of the Sun that already basks the Earth in life-giving light and warmth. Converting the Sun's radiant light and heat into electricity with relatively small roof-mounted solar arrays simply redirects the energy that would have warmed the surface of the roof to electricity that can power the home and transportation[4]. This simple and cost-attractive package immediately removes more than half the climate footprint of the average American, and in a manner that will not interfere with the delicate balance of Earth's natural cycles and fragile ecosystems[5].

With clean energy powering the home from onsite solar PV, it completely changes the calculus on efforts to reduce heat loss and energy. Using less energy is still preferable, because it could mean fewer resources needed to install a smaller PV system, though this argument requires a significant distinction about energy reduction methods. Demanding less energy by lifestyle choice, such as building and living in a smaller home, or driving less, has ecological benefits with no offsetting environmental damage. However, attempting to demand less energy by scaling up the thermal envelope, with the aim of reducing heat loss, does measurable ecological harm in materials use (embodied energy). Additionally, this study shows very poor (and actually negative) financial returns on nearly all thermal envelope upgrades, even if they were to achieve optimistic performance claims. Our data, however, demonstrated very little--and in some cases no--operational energy benefits for upgrades beyond code-minimum standards (if built with

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[1] As of 2019 Alaska and a small area of the Pacific Northwest do not have the climatic endowments (given current pricing and technology) for solar PV to compete with equity markets over the long term (see Chapter 3). Financial returns on solar PV are still likely to be far better than returns on thermal envelope upgrade investments, and still have overall ecological value in displacing fossil fuel-based energy.

[2] Beyond building code requirements for structural integrity, safety, and minimal levels of insulation.

[3] All stars burn out in time; when the Earth's Sun dies, none of this matters, given the current limits of human knowledge and imagination.

[4] Assumes fully electric vehicles (EV) charged from home-based solar PV systems (see Chapter 7).

[5] Recognizing the impact of buildings, vehicles, and roads on nature but assuming Americans are not willing to forgo these features of modern life.

quality), and we employ the logic of diminishing returns, weak links, and mismatched elements to explain this surprising reality. We also discuss the opportunity costs of thermal envelope upgrades as further reason to resist that energy-reduction method.

Building codes in the U.S. require minimum standards for structure and safety, and then insulation R-values consistent with filling structural voids, such as in stud, truss, and joist cavities. The building science on insulation efficacy is robust and clear, and that points to code minimum levels already at or beyond cost-benefit optimums; in other words, adding more insulation beyond code-prescribed minimum standards (especially in walls and ceilings) provides little if any benefit, but at measurable costs. The overall assessment of thermal envelope upgrades beyond what code requires, shows very poor trade-offs between embodied energy in the upgrade (significant) and operational energy saved (little to none). The analysis is very different with solar PV, which has excellent cost-benefit metrics in any size, and while scaling up; the embodied energy in materials[6] is low relative to operational benefits (clean energy production) for more than 30 years.

The inertia of conventional wisdom is strong and persistent. Even though onsite solar PV[7] changes the calculus of thermal envelope choices, we find that industry professionals still struggle to comprehend these trade-offs. For example, some question whether it is it better to upgrade the thermal envelope for the sake of a smaller PV system, or plan for a larger PV array with no thermal envelope upgrades? To be clear, we found no financial or environmental support for upgrading walls[8] or ceiling R-values beyond code-minimum. Even if thermal envelope upgrades were successful in reducing heat loss and energy use significantly, the embodied energy costs to operational energy benefits are magnitudes worse for thermal envelope upgrades than for solar PV in any size, and while scaling up. We do offer recommendations for best practices in meeting code requirements of the thermal envelope, including insulation type and application, utilities in exterior walls, and prioritizing weak links if any attempt is made at upgrades (see Chapters 5-7).

The surprisingly weak support for thermal envelope upgrades beyond code minimum standards applies similarly to equipment and appliance upgrades beyond basic models. The embodied energy costs of upgrades fail to be offset by any operational energy benefits over the expected life of the equipment, and dollar cost premiums for upgrades almost never return break-even

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[6] National Renewable Energy Laboratory (NREL) estimates that energy produced by solar panels offsets the energy used to produce them in four years for polycrystalline and two years for monocrystalline. Another crude but intuitive measure of embodied energy is weight; two examples of solar PV systems in 2018 were 1,600 lbs. for a 5.8 KW system (modules, racking, inverter, wiring, etc.) and 1,897 for 9.1 KW system. These weights pale in comparison to thermal envelope systems for a whole house.

[7] Other clean and renewable energy sources could be substituted here; we use solar PV as a proxy because of its proven merits, widespread availability, and known environmental and financial benefits.

[8] Code compliant 2x4 wood stud walls are adequate if utility boxes and pipes are kept out of exterior walls; this may require some surface-mount outlets and switches (see Chapters 5-7). If stakeholders are unwilling to hold utilities out of exterior walls, we recommend upgrading to 2x6 wood stud, with recognition of the increased dollar and environmental cost at construction.

payback during the product life. It is possible that new technologies and innovations in the future could bring to market products that refute this claim; however, in 2019 there is no financial or environmental support for upgrades to equipment and appliances. There is a special case for addressing ventilation that may require equipment beyond what building codes prescribe; this is needed for adequate air exchange to avoid unhealthy indoor CO_2 concentrations; see Chapters 6 and 7 for details on all energy systems.

The overall implication of this study suggests a new combination package for how Americans build (or renovate) and equip their homes. This starts with a priority for onsite active solar of sufficient size to power entire household operations, and we recommend additional sizing and production to power household transportation with EVs. The choice of home-generated energy in lieu of purchasing from the electric utility[9] will reduce[10] homeowner energy costs. A home designed under a solar capture zone (roof) can then be built to code-minimum standards, with care and attention to quality in the details. This will cost the homeowner tens of thousands of dollars less than constructing thermal envelope upgrades, most of which worsen both financial return and overall environmental impacts. Base level equipment and appliances can be selected, knowing that whatever energy they draw will be onsite-produced with clean and renewable solar. Each one of these elements--solar, envelope, and equipment--are the least costly financially and environmentally. Furthermore, this package is more likely to appraise at constructed cost than alternative models, improving financing, affordability, accessibility, sellability, and return on investment.

Two of the three elements have been within our grasp for decades, yet insufficiently understood to drive action toward the more sustainable choice. While solar PV has only recently become less expensive than public utility rates[11], the efficacy of thermal envelope, equipment, and appliance upgrades on both financial and environmental grounds could have been uncovered with relatively simple financial tools and actual installed performance data. In this study it was learning about the attractive lifetime costs of onsite solar PV that reoriented our minds around the related elements of thermal envelope upgrades, and equipment and appliances above base units. Homeowners may desire upgrades for a wide variety of reasons such as comfort or aesthetics. However, financial return and environmental responsibility need to be disaggregated from those other objectives; simply stated, the upgrades available in 2019 do not return financial benefits, and most have much worse environmental impacts over the life of the product.

Significance:

These findings are enormously significant. Precious few homes built and renovated today even attempt to achieve climate-neutrality in operations. The industry is entrenched in the idea that the thermal envelope needs upgrades well beyond code minimum standards as a first step. When homeowners plan or act with thermal envelope upgrades as priority, they quickly

[9] Assumes grid-tied system with net meter and close to net-neutral long-term reconciliation.
[10] See Chapters 3 and 7.
[11] Solar PV less expensive than utility rates over the life of the system (see Chapter 3).

accelerate costs, which too often pushes onsite solar off the table. Remember that our analyses demonstrate that thermal envelope upgrades actually achieve little or no benefit in reduced heat loss and energy use, so the very expensive premiums become sunk costs with negative returns. Further, thermal envelope upgrades almost always push constructed cost above appraised value; this worsens and complicates financing, resale, and return on investment. Only the wealthy can afford this type of financial package, and the building package actually worsens overall and lifetime environmental impact.

Surprises:

The findings of this study turn the tables on thermal envelope upgrades, as well as selection of equipment and appliances. We also demonstrate the lifetime cost of onsite solar PV as less expensive, and much less environmentally-damaging, than electricity drawn from most public utility grids. Those revelations are surprising indeed, yet the biggest surprise from this study is that the best environmental choice is also the best financial choice, and the least costly option. Conventional wisdom assumes trade-off relationships between finance and ecology, yet this study proves congruence between the two. The relatively small additional step of ensuring enough solar production to also power electric vehicles will also reduce lifetime transportation costs (see Chapter 7) and make another significant dent in the household climate footprint.

Our team had studied the industry, and in particular the green building movement, and we knew of the significant cost premium of scaling up the thermal envelope. We also had been compiling the vague performance claims of thermal envelope upgrades, and we had not yet encountered analysis that accounted for the environmental externalities of energy generation. We set out to test whether adding the externality to the cost of energy (used or saved) would make a case for the cost premium of upgrades at construction. Using the tools of environmental economics, we expected (and hoped) to find that accounting for environmental externalities over reasonable time frames would make envelope upgrade investments economically viable; that would make the case to build more sustainably by making the big recommended investments at the outset with expected returns over time.

Our first surprise, using the tools of both environmental economics and finance (cost of funds), was that the cost of most upgrades to the thermal envelope were so high that there was no chance of receiving economic payback, even when adding environmental externalities. We then set out to test the performance claims, which led to an even bigger surprise; thermal envelope upgrades result in little to no energy performance benefits[12]! We do not doubt the performance claims of lab-tested products and systems, but our data suggested that other factors mitigate potential benefits when packaged in a whole house, lived experience. This led us to conceptual theory that a combination of diminishing returns, weak links, and mismatched elements progressively weaken any potential benefit from the strongest elements. Finally, on the basis of lived performance data, we evaluated embodied energy impact of thermal envelope upgrades

[12] See Chapters 5, 6, and 7 for details.

against operational energy benefits; this whole-house, lifetime assessment is more consistent with the perspectives of ecological economics, and that also added to overall findings and conclusions.

As we began to uncover the surprising results that thermal envelope upgrades do not actually save much energy, if any at all, we were also discovering the surprisingly strong financial and ecological case for onsite solar PV. Connecting these dots provided the final key to unlock the surprising win-win package of the SOLO house; solar energized, and low cost construction[13]. When all household energy is provided by clean and renewable onsite solar PV, suddenly envelope upgrades are not only not needed, it highlights the harm they cause to the environment in materials use and unnecessarily more embodied energy.

Reason for surprises:

There does not appear to be a grand conspiracy to defraud homeowners of their resources, or to block progress toward sustainable housing. Rather, it seems that the building industry has simply lacked the tools and application of finance and ecological economics, which now point to very different directions and outcomes. Another contributing factor is that performance data is difficult to obtain in real life; that is, in the lived experience of constructed and occupied homes. Without actual packaged results, the building industry is left to rely on lab-based and unit-based testing, which may be accurate in those conditions, but seems skewed optimistically when part of a mixed (real) environment.

We hope that another contribution of this study will be to encourage stakeholders to apply the concepts of diminishing returns and opportunity costs to choices in the home building, buying and selections process. A simple example of wall insulation illustrates both concepts. In most U.S. jurisdictions, R15 is the building code minimum standard in walls. That *minimum* level of insulation achieves 95% reduction in heat flow through a perfectly-installed cross-section of the material; that is the most effective insulator in the wall, which also has much weaker links from structure, windows, doors, and other features. Adding thickness to the wall and insulation can increase R-value to R32, which leads many to believe that the choice will be twice as effective at reducing heat loss. However, due to diminishing returns and proximity on the R-value scaled curve, R32 achieves only two points better than R15; 97% heat flow resistance compared with 95%. Relative to R15, R32 is only 2% more effective than the code-minimum wall, and when weak links and mismatched elements are included in an actual packaged installation, that small improvement in the best-insulated element is diminished still further[14]. This helps explain why actual performance data shows very little benefit for upgrades to the most insulated elements of the thermal envelope. The thicker wall achieves negligible benefit for a significant cost in both materials use and dollars.

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[13] We wish to keep reminding that low-cost does not mean low-quality. A code compliant house can be constructed with care, integrity of process, and verified through objective third-party inspection.
[14] See Chapter 6 for impact of weak links and mismatched elements on strongest insulation sections.

Upgrading from R15 to R32 walls is likely to add tens of thousands of dollars on an average sized home, and this is where opportunity costs are relevant. The money NOT spent on wall upgrades could have purchased onsite solar to power both home and transportation and the transition to electric vehicles. It is clear which choice is better for the planet, and powering home and vehicles with onsite solar PV will also save money for the homeowner. Since R-value in insulation and U-factor in windows is so misleading in its current scale, we propose a wholesale recalibration of the metric on the basis of heat flow reduction. This would place windows, doors, and wall and ceiling insulation on a similar scale between zero and 100%, and it would more accurately reflect the relative value of products and choices. Heat flow resistance does vary with conditions, though not dramatically, and the R-value metric does not currently account for that variance. A recalibrated scale could be benchmarked on most common or average-use conditions, with variances allowed for extremes. If changing the R-value scale is too disruptive, we recommend renaming to *insulation value* (I-value) or *heat resistance value* (HR-value).

Implications:

While we were initially disappointed that our expected findings did not materialize, the surprising results of our study took us to far better outcomes than we could have imagined. Overall, building a solar-powered low-cost (SOLO) house is least costly in dollars and resource use, it fully removes climate emissions from household energy and transportation (with home-charged EVs), it is more likely to appraise and finance comfortably, it will have market advantages on resale, and it is likely to offer the best return on investment compared with non-SOLO homes. This makes a net neutral home desirable to everyone and available to anyone[15]. Solar PV is economically advantageous now, and costs continue to fall. Even without any care for the environment or the planet, U.S. homeowners should be driving for home-produced solar energy because it will save (and make) them money; fortunately, it also offsets energy from utility grids that is produced in ways that are harmful to the planet (fossil fuel-derived).

The findings of this study unexpectedly pointed to a convergence of economic and ecological interests; what is best for the planet is also best for the pocketbook, and with climate emissions from operations off the table[16], environmental priorities then turn to embodied energy, durability, and decommissioning. Simpler, less costly, and less invasive building systems and equipment will be easier on the planet, both when constructed/manufactured and at end of life. This paradigmatic shift of thinking also has encouraging implications for existing homes. It is always worth plugging holes or sealing cracks in the building envelope, but it may not be necessary (or even desired) to tear down and rebuild, or engage in costly and invasive renovations. The sequence of prioritizing onsite renewable energy first will almost always point to less costly and less material-intensive rework of the structure and insulation; that not only preserves both environmental and economic resources, but it can help preserve history and culture.

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[15] Home ownership accessibility expands with the SOLO house because it is no more costly to construct than code-compliance today, and operational costs are reduced.

[16] Cost-beneficial solar PV would remove climate emissions from housing and transportation for many Americans.

One final note about code-minimum construction, which tends to be 2x4 stud wall structures: the insulating cavity is too narrow to sacrifice cutouts for fixtures or piping. If 2x4 exterior walls are selected, allow no impingements into the insulation cavity. In other words, make sure the full width of the cavity is maximized for insulation. While electrical wiring can be accommodated in the cavity with careful insulating, outlet and switch boxes are notably egregious in displacing insulation. Outlets could be placed in the floor instead of exterior walls, or with surface-mount fittings integrated with baseboard and/or trim[17]. Plumbing pipes should route through the floor or interior walls to keep those intrusions out of the insulation plane. Failure to adhere to these recommendations will unnecessarily add weak links to the thermal envelope; it can also create channels for mixing cold and warm air, leading to condensation, potential mold growth, and possible structural compromise. Even for 2x6 exterior walls, surface-mounting should be considered in the interest of limiting or minimizing weak links in the thermal envelope.

Reactions and Responses:

Since we are advocating a complete paradigm shift in thinking and action in how we build and power homes in the U.S., we expect strong reactions and responses. This section attempts to predict reaction from various stakeholders and offer directed information or rebuttal to expected questions and critique. This is not meant to be defensive, but rather to extend further dialogue in the interest of broader discussion and understanding.

Environmentalists are likely to react initially with a visceral reflex against this new paradigm. We fully understand that emotion, because we experienced it ourselves. This may be the first case of doing better for the environment by doing less to save energy. The environmental movement pushed, with good reason at the time, for energy efficiency in products and systems; in housing, that resulted in expensive and complex equipment and appliances, and premium upgrades to the thermal envelope. However, by prioritizing onsite clean energy production, we do not need or want the extremes of energy savings through efficiency, since that path has significant negative environmental impacts in embodied energy and for other reasons described in this book.

Unfortunately, the current paradigm encourages environmentally-conscious people to spend their housing budget on upgrades that may reduce their energy use only slightly, if at all. Having then exhausted their limited resources on upgrades as a first priority, and having further taxed the environment in materials use and embodied energy, they miss the opportunity to make the biggest impact of all; cutting their overall climate emissions in half by adding solar PV to fully power home and transportation. Adding further discouragement, our finding showed no upgrade cases (except LED lighting) that would return the upgrade investment in operational savings, and we also found operational savings do not meet claims (details in Chapters 5-7).

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[17] See examples of surface mount electrical outlets and switches in the case home (Chapter 5).

We invite environmentalists to read the details of this book with an open mind, and test these findings and theories with their own independent research. We have placed our data and calculators on a companion website[18], not only for transparency, but for widespread use and verification. The new paradigm we propose requires an assessment of the whole system; the forest, if you will. The current orthodoxy's focus on individual trees misses the point of the forest, and pushes a model that worsens resource use and embodied energy, and offers little or no headway on reducing operational energy; it has not offered climate solutions anywhere close to what can be achieved with the SOLO house. We think environmentalists will come around on this counter-conventional thinking and eventually push a strong transition into the mainstream.

Homeowners who recognize the ecological predicaments of our time, and who attempt to make progress in reducing their personal environmental harms, will celebrate this new paradigm. It will not be difficult to sell environmentally-conscious homeowners on a package that completely removes climate emissions from their energy footprint for housing and transportation, especially when they learn that it will cost them *less* and include the desirable transition to EV driving[19]. Since everyone would rather pay less for the same level of service, all homeowners--regardless of environmental commitment--should embrace this model if the overall financial benefits of solar PV can be communicated effectively. We recognize the complexity of valuing a large present expense against a long-term stream of benefits; we suggest using a monthly outlay comparison assuming a loan-financed PV system. In these cases, most homeowners will pay less each month to service a solar loan than the comparable monthly electric bill it will replace.

Upgrades are currently touted and sold on environmental responsibility; most also have comfort and/or aesthetic virtues. It has been convenient for homeowners of relative wealth to be able to cloak (or claim) choices of luxury in environmental responsibility. Such wealthy homeowners may not appreciate this analysis, because it disaggregates sustainability from luxury and comfort; now we know that the luxurious choices are more environmentally damaging. Other than the upgrade to LED lighting, this new paradigm suggests the more responsible choice for less ecological harm is solar PV as priority, a thermal envelope built to code (with quality), and basic equipment and appliances. That overall package is far less damaging to the planet than the alternatives, even if homeowners set their thermostats 3-4 degrees warmer in winter months. We are not suggesting that aesthetic upgrades should never be selected. Rather, we suggest that those choices be made with the full knowledge of environmental impact; that also adds further rationale for home-generated clean energy to help offset higher embodied energy.

People often compare the more desirable warmer heat of gas against relatively cooler air from heat pumps, and that is notably felt at the same ambient temperature and indoor humidity. However, indoor warmth can be achieved with a heat pump if the thermostat is set high enough for personal comfort, and that is still the far better choice from an overall ecological impact perspective than direct use of a fossil fuel. And just as it is better for the planet to run a

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[18] See: https://www.sustainableclimatesolutions.org/housing

[19] Thanks to Tesla, and other recent manufacturer entries into this market, EV driving and ownership is becoming preferable to the legacy technology of internal combustion engine (ICE) vehicles.

solar-powered heat pump a few degrees warmer in the winter, it is also better to enjoy warmer indoor temperatures in a code-compliant house than to bulk up on building upgrades. The author shares some personal experiences in the Case Project section.

The new paradigm will expand accessibility of home ownership, especially to those of meager means. Transition to these protocols will lower the cost of new construction, and more closely align actual costs to appraisals and financing opportunities; that will open home ownership to more individuals and families. Second, this will have the added benefit of lowering the cost of existing homes, over time, and also lowering the cost of renovations. While low-asset and low-income buyers could not afford to add costs associated with environmental responsibility under the past paradigm, the SOLO home provides that feature as a complementary benefit. Overall, all homeowners will embrace the new paradigm for lower costs initially and operationally, and some for the environmental byproduct. Environmentalists will eventually advocate a speedy transition to this new paradigm for the promise of dramatic reduction in climate emissions and a smaller footprint on resources.

Most builders are likely to embrace this new paradigm, as many did not immediately or easily jump to the trend of scaling up thermal envelope elements. This group will be least disrupted among stakeholders, since they can continue to operate much as they have for many years; adding solar PV is as simple as arranging or contracting with a third-party installer. However, for the minority of home builders in the U.S. who embraced the premium home concept, and built market share on that differentiated niche, this analysis will be difficult to swallow. Since premium home builders are also known (often) for quality construction, we think there is still a market for this group, but now pitched more for quality, integrity, durability, and longevity, rather than on energy efficiency. Given that the SOLO house is carbon net neutral, and uses fewer resources, and is less costly to build, it will be difficult for premium home builders to match any of those qualities and claims.

Architects and engineers study building science primarily from lab-based and unit-based testing, and that lacks the complexities of installed mismatched systems. These professionals will need to rethink and reorient, but we are convinced they will make the transition quickly. Since the SOLO house can be constructed at competitive costs, there may be more room in building budgets for architectural services, and their work could focus more on design and gaining space efficiencies rather than on building systems, materials and energy efficiencies. Architects could develop a niche for helping homeowners size PV systems to meet the combined energy needs of home and transportation, and navigating the application and approval process through utility and building permit agencies. Architects could also pitch their services using the new paradigm as a way to inexpensively achieve both functionality and climate neutrality. If passive solar is added, an architect will be invaluable for orienting and designing the structure to maximize solar heat gain, calculating the correct shading angles, and advising on possible heat sinks.

Public utilities are likely to feel the most threatened by this new paradigm, as it will progressively reduce their service and revenue base. The early stages of scaling up distributed solar is beneficial to most regional electric utilities, as peak solar production initially coincides with--and offsets--overall utility peak demand from commerce (business day) and air conditioning (summer afternoons). Beyond critical thresholds, however, increasing levels of distributed solar shift peak demand to low/no solar production periods and widens the demand variance. For example, morning and evening hours eventually become peak demand periods when solar production is low or none; this creates a challenge for utilities to manage their energy generation or purchased portfolio in the public interest. As challenging as that may be for public utilities, we collectively need them to operate in the public interest, which includes future generations in addition to current customers.

Public utilities should be willing to make this transition work. Utilities that operate in their parochial self-interest, instead of accommodating a viable path to dramatically lower climate emissions, will encounter stiff and adversarial resistance from a broad set of stakeholders. We hope public utilities will recognize the inevitability of the transition to cleaner energy and work collaboratively with customers in the spirit of the public good. Exploring clean energy and storage in their own portfolios could hasten the transition to clean energy, and possibly the long-term viability of regional utilities. This new paradigm is very bad news for direct fossil fuel utilities (oil and gas), and we expect they will find ways to criticize and resist.

Public regulators will feel caught in the middle between constituents and opposing interests; they are also uniquely situated where they have a powerful and influential voice in both policy making and implementation. Given their unique perspective and setting, we expect the pace of transition to roughly mirror the movement of this group. As with utility interests, we invite public regulators to operate in the public interest, including future stakeholders.

Further Research:

As with most research projects, this one unearthed new and further questions to be explored in subsequent work, which we list in this section as encouragement to ourselves and others. The primary advancements of this study change our understanding of solar PV, thermal envelope systems, and the relationship between the two. Onsite solar PV is shown to be both financially and ecologically effective and advantageous at current prices and technologies; however, both of those metrics are evolving continuously, requiring ongoing analysis. While we expect distributed solar to grow even more attractive in the future, there are uncertainties in areas of trade policy, investment incentives, technological change, and regulation that could alter the calculus in either direction. We do not even know with certainty how long PV systems will continue to operate beyond warranted periods, and at what production levels; this reflects relatively new technologies and dramatic improvements just in the last decade. Ongoing analysis of that data is needed to update financial models and refine our understanding of life-cycle embodied energy in the various components. We also hope to see more focused studies on recycling of solar modules and inverters.

Many questions remain about thermal envelope systems. This study found surprisingly small levels of efficacy in energy savings by thermal envelope type when actual data on whole house, lived experience is compared. Our team compiled a database of homes in a single region to compare the performance of thermal envelope systems in similar climatic conditions. While our sample size was large enough to draw broad conclusions on several specific systems, we plan to continue adding cases to allow more robust statistical analysis on across a broader range of building packages. We also hope to develop formulas to control more precisely for known variances, such as number of occupants, and the presence of a well pump, for example. Another line of research should explore the specific cost of wall thickness beyond code compliance; in addition to the cost of the wall materials, a thicker wall requires an enlarged foundation and/or slab, enlarged roof structure and cover, and more exterior finishes such as siding, facia, soffit, gutter, and other elements. Finally, we would like to see research that quantifies the impact of weak links, and specifically their contribution to overall heat flow through thermal envelope planes, and then the influence of that impact on the performance of stronger elements. Based on our whole-house comparative analyses, we suspect that knowledge will be the key that unlocks the mystery of thermal envelope performance.

Public Policy

Governments, regulators, and public utilities are tasked with improving the well-being of their constituents while serving the public interest and societal good. The paradigm shift we propose will serve those objectives in three distinct ways; it will reduce materials use and waste from the construction industry, save homeowners money in housing expenses, and it will cut overall climate emissions in half. Even if climate deniers are not interested in reducing greenhouse gas emissions, the SOLO house concept should still be supported on personal finance and regional economic grounds. Homeowner savings from house construction or purchase price, as well as from lower operating energy expenses, will be reallocated to other economic activity and benefit other areas of the regional economy. And less waste to landfills and recycling centers will lower those public expenses. In this section we offer a number of policy suggestions for public officials and agencies to encourage, accommodate, and/or incentivize this transition in support of the common good.

The first priority is to ensure an accommodative regulatory environment for residential solar. Many electric utilities, both public and private, have gained notoriety for resisting distributed solar and erecting barriers for homeowners; that action may serve the utility, and legacy fossil fuel interests, but it does not serve their individual constituents, and it certainly does not serve the public good. Home-based battery storage technology and costs may improve enough in the future to make off-grid independency viable, but a connected network is likely to have both economic and ecological advantages of sharing surplus production and economies of scale on both storage and new energy production when needed.

Recognizing that utilities will face logistical challenges as their energy portfolios shrink, and as they also transition to cleaner energy sources on commercial scale, we advocate strong public support for utilities that help them navigate these changes while also supporting distributed solar. Placing restrictive caps on PV sizing, and/or charging exorbitant connection or standby fees, is not in the public interest. A policy that eliminates system size caps and connection fees, and offers customers a discounted wholesale rate for any surpluses they wish to cash out annually, will benefit both parties, and the common good. Homeowners could install enough solar to sufficiently (net) power their home and transportation; if they size too large and run surpluses, they could bank the credit or cash it out annually. There would not be an incentive to grossly oversize because any sale of energy to the utility would be at a steeply discounted wholesale rates (consider 50% of wholesale); there would be no economic incentive to become an energy producer beyond what is individually needed. Utilities would benefit by receiving some surplus energy at no cost (if homeowners bank or donate the credit) and some surplus energy at highly discounted rates; that would also benefit non-solar customers by lowering their rates. Society gains from a dramatic reduction in climate emissions; this benefits all customers today, both solar and non-solar, and future generations for centuries.

Homeowners who come to recognize the financial benefits of generating their own clean energy onsite will act on their own as long as there are not impediments. The electric utility environment is noted above, but homeowner conditions also need to be adequate from an orientation and obstruction standpoint. We discuss this in greater detail In Chapter 4, but here we will mention that the public interest will be served by influencing or incentivising development design, and community easements and covenants, in support of distributed solar. Generally, conditions should promote buildings with unobstructed exposure to the south, and ideally an east-west long axis orientation to maximize solar capture on the south for active and possibly passive solar. Neighborhood road networks and building plot size and orientation is the first step, and then easements and covenants can work at maximizing privacy while minimizing potential shading problems (see Chapter 4 for greater detail). This form of policy accommodation is much easier with approving new development, but it can also be incentivized for many existing communities that can transition to distributed solar over time.

In California and Arizona, where distributed solar is more common, and better supported by public policy, the value of installed solar PV is routinely included in home appraisals. Valuing productive solar systems is relevant for seller, buyer, and financing, but unfortunately it is not common practice in most states, even though it is provisioned in U.S. national appraisal guidelines. Because the PV system will continue to provide a stream of benefits to the new owner, it has economic value and should be included in appraisal, sales price, and financing. Secondly, it further incentivizes solar installation when homeowners have confidence in recovering their investment if they move before the system fully recovers its initial cost. In early 2018, California became the first state to pass a law requiring all new homes to install solar PV (Penn, 2018). It takes effect in two years, allowing stakeholders time to prepare for the change, but this strong public position recognizes that it is in the interest of both homeowners and the public good.

Currently an investment tax credit (ITC) for new solar PV systems improves the economics for home installations, though the current provision is set to phase out over the next several years. We expect PV prices to continue to fall to the point where the ITC will no longer be needed for economic incentive; however, public interest may support extension of the ITC in the interest of the known environmental benefits. Another approach would be to disincentivize competing *dirty* energy sources, and specifically energy derived from fossil fuels. Economists, in their quest to *get the price right*, push to include the cost of externalities and advocate a user fee, or in this case, a carbon tax. Unfortunately this concept has been politicized in the U.S. to the point of toxic poison, but perhaps knowledge and understanding can overcome that resistance with strong education and awareness efforts.

Regarding public policy on thermal envelope choices, building code officials have mostly resisted the push to scale-up minimum standards. Since our findings show very little benefit in scaling up the strongest elements, and since we know the dollar and embodied energy costs are high, our suggestion here is for public officials to hold firmly to the current building code requirements for the thermal envelope. If the transition to solar PV takes root rapidly, meaning that energy to power home and auto is generated cleanly onsite, officials might even wish to support research to check whether current standards may be too high. Further research and understanding on the raw and relative impact of weak links may change the calculus for requirements of the most insulated elements of the thermal envelope--walls and ceilings--and may also inform new standards and code on minimizing the impact of weak links.

Public Service Announcements (PSAs) on the economic and ecological impacts of code construction and alternatives might also be developed to inform constituents. For example, a brochure attached to each building permit application, and published on the web, would extend distribution of this important information. Finally, we have advocated (above) for a recalibration or replacement of the R-value metric to provide better information and understanding of the relative value for different insulating levels. This will need the support and advocacy of many stakeholders, and most notably from public officials.

Case Study:

The case house was designed for what we thought was the most environmentally-responsible way to build a modern mid-sized American home; this was largely in alignment with prevailing building science and conventional wisdom in the industry. We began construction while also collecting primary data for new analysis on different variables and scale. While disappointed in our initial discovery that including externalities does not provide rationale for significant thermal envelope investments, we were stunned to observe that the tools of finance are largely absent from the literature and understanding on building choices. When we applied the cost of funds and energy inflation to these choices, it led to the dramatic surprises we have written about in this book. Some of our surprise findings emerged in time to alter course on the case home, but the data arrived too late to change the big commitment to a premium thermal envelope.

The thermal envelope has now become one example of what we do not recommend, but the case house did provide a fantastic comparison in several helpful ways. Recall that the case house used thick ICF walls, 12-14 inches of spray foam insulation in ceilings, and triple-pane fiberglass-framed casement windows. The homeowner had been living in a code-minimum house of similar size, in the same neighborhood, offering a comparison between minimum and maximum thermal envelopes in the same climate. While our surprising data on whole house energy use from a sample of regional homes was already forcing us to question the efficacy of thermal envelope upgrades, the final confirming and convincing data came from comparing energy use in these two houses, with the same occupants and same energy behaviors. We would not be making this case with as much confidence and strength if not for this personal and direct experience, where we controlled for most variables, carefully monitored and measured data, and had personal finances at stake. You can read more details in Chapters 5-7).

These two houses also gave the homeowner the opportunity to test and compare the comfort level between minimum and maximum thermal envelope. In addition to claimed energy savings, premium homes are sold on premium comfort, touting more consistent temperatures throughout the house, and less drafty. From my experiences, I simply refute this claim; it has been no more comfortable in a house with a premium thermal envelope than my previous residence in a code-minimum structure at the same indoor temperature. Both houses have similar weak links, though the case house has much better windows. Still, the sense of cold in the winter comes from the weakest links, and not through the relatively better insulated walls, and overall comfort is more consistent with indoor temperature (thermostat setting) than with thermal envelope type. Even distribution of heat has more to do with quality design of the ducted forced air system and number and quality of weak links in any given space. Stated more directly, the greatest indoor comfort will come from the thermostat setting rather than the wall type, and if the energy powering the HVAC system is clean and renewable, it is not as important to sacrifice comfort with less than desirable indoor temperatures.

The case home is fine from a livability standpoint. We understand this only in retrospect, but we could have built a code-minimum home to be equally livable. The more basic thermal envelope would have used fewer resources, and cost more than $100,000 less. I have come to realize that this will be a difficult house to sell, that potential buyers may not get the appraised value they need to finance the expensive house, and my financial return on investment will be very poor. Now consider the opportunity costs of the premium thermal envelope; $100,000 would have easily transitioned the household to EV transportation. We thankfully planned for solar PV from the outset, but if the house had taken my last dollar, solar PV would have been a regrettable sacrifice. And if I desire a more comfortable indoor experience, $100,000 would easily fund any extra energy to set the thermostat a few degrees higher in the winter.

Summary and Conclusions, and the Future:

Since this chapter is largely summary and conclusions of the entire book, this space will used for a glance at future possibilities related to this work, and a final pitch for opportunity costs. It is amazing that all of the Earth's energy comes from one source, the Sun. Until 200 years ago, humans lived mostly on a daily dose of sunshine; life was simple, and population remained low and dispersed. Then we discovered *stored* solar energy in the form of fossil fuels; this spurred industry, mechanization, transportation, and eventually economic surplus and arts and culture; modern life. Fossil fuels also improved agriculture and allowed human population to explode; unfortunately, these combined factors also stressed the environment and caused climate imbalances. We live in an incredible time of threat and possibility, and hopefully at the turn from stored solar energy to once again living on a daily dose. Solar PV at commercial and residential scale and competitive cost is now less than a decade old, and yet it appears capable of supporting modern life for 7.7 billion people on a daily measure of sunlight. The paradigm proposed in this book demonstrates both the capability and affordability.

Solar cells and batteries are now showing up in a wide variety of products, from flashlights to exterior lights, to the warning signs along highways. We expect that to grow more prominent in use, even as it become more hidden from view. As of this writing Tesla Energy is marketing a first generation solar shingle; they are more expensive than installing panels, but we think prices will fall and this direction is inevitable. We even expect prices to fall to the point where orientation to south will not be critical for economic payback; that will make solar shingles viable for nearly every roof, new or old. Agressive public support and policy can expedite that evolution. The action by California to require solar on new buildings will speed this process, and we expect more states to follow this lead.

With every house powered by clean solar energy, it makes even less sense to upgrade the most insulated components of the thermal envelope beyond code-minimum. However, we believe there is great room for improvement in the weakest elements of any building; windows, doors, and the many penetrations through walls and roofs. We might discover that the best way to improve window and door weak links is a basic unit with added insulated interior treatments. In retrospect on the case home, I would have installed a more standard window and used some of the saved upgrade budget on window quilts. Home automation is expanding rapidly, and mechanized and/or programmed insulated window treatments could become functional and practical to use, while improving heat transfer even with basic windows. Seals around doors and windows, and more effective damping of fan pipes would give homeowners and the environment the best bang for the buck. With every new innovation and product, it will be important to consider the overall ecological impact, including resource use and embodied energy, against any operational energy savings. Astute stakeholders will also consider the opportunity costs.

In the U.S. today, new houses can be constructed in most markets for less than $100 per square foot, if built with code-minimum structure and basic equipment and appliances. The industry and many environmental interests have pushed a more robust and complex house in the name of energy savings; however, those systems require many more resources and can run the cost of new construction well above $150 per square foot. Using those conservative unit prices, consider the opportunity costs at five sizes:

Size	$100/SF	$150/SF	Difference
1600 SF	$160,000	$240,000	$80,000
2000 SF	$200,000	$300,000	$100,000
2400 SF	$240,000	$360,000	$120,000
2800 SF	$280,000	$420,000	$140,000
3200 SF	$320,000	$480,000	$160,000

What could be done with that difference? Even at the smallest size, a homeowner could add enough solar PV to power both home and transportation, and purchase a new long-range electric vehicle (EV). There would even be funds remaining to contribute to programs that help the poor most impacted by climate change and least capable of adapting to the scourge. How did we get here? We hope this resource is helpful in your own choices, and how you advocate for change in your community; best wishes in your quest to become more sustainable, for yourself and others. For ideas on reducing your ecological footprint beyond housing and transportation, visit the companion website at https://www.sustainableclimatesolutions.org/housing.

Finally, while this research was focuses specifically to conditions and markets in the United States, the same principles can apply to other regions of the world, and notably to the similar latitudes of Europe and Asia.

Dos and Don’ts:

Dos related to conclusions and a look to the future

1. Prioritize and plan for solar PV first, even though installation is last
2. Size solar PV for enough production to power both home and autos (EVs)
3. Build code-minimum structure, with quality, for best financial and environmental impact
4. If there any thermal envelope upgrades are attempted, start with weak(est) links
5. Advocate to public officials to develop accommodative environment for residential solar
6. Look to the future with hope for the potential dramatic reduction in climate emissions

Don’ts related to conclusions and a look to the future

1. Don’t fail to prioritize solar PV (budget, house orientation, capture zone, etc.)
2. Don’t select thermal envelope upgrades in the name of environmental responsibility
3. Don’t select upgrades of any kind without considering the opportunity costs
4. Don’t fret setting indoor thermostat to your comfort zone if energy is from clean solar
5. Don’t assume that bigger/thicker/more is always better in wall systems; it is not

Chapter notes:

National Renewable Energy Laboratories (1999), *Energy Payback: Clean Energy from PV*, Available at URL: https://www.nrel.gov/docs/fy99osti/24619.pdf

Penn, Ivan (2018), *California will Require Solar Power for New Homes*, New York Times: May 9, 2018, Available at URL: https://www.nytimes.com/2018/05/09/business/energy-environment/california-solar-power.html