CONSTRUCTING A NET ZERO HOUSE

AFFORDABILITY VS SUSTAINABILITY IN NET ZERO HOUSING

A Thesis Prospectus

In STS 4500

Presented to

The Faculty of the

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In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science in Mechanical Engineering

By

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Housing is a large source of energy consumption in the United States and globally (*U.S. Energy System Factsheet, 2021*, para. 2). Many houses are inefficient at least partially due to the comparatively high upfront costs of energy efficient technologies (D'Agostino et al, 2020, para. 58). The technical topic involves creating a house that produces more energy than it consumes while minimizing greenhouse gas emissions while keeping costs relatively low. The technical project is currently being advised by Professor Harsha Cheliah from the University of Virginia Mechanical and Aerospace Engineering department. Twelve undergraduate 4th Year Mechanical Engineering students will work together with Professor Harsha Cheliah. The 12 students working on this project are Luke Anderson, Lucas Daugherty, Alex Davis, Jillian Doyle, Max Gerber, Amelia Kokernak, Kara Koopman, Isaac Mulford, Cathryn Palmer, Jack Pazin, Noah Plues, and Joshua Starr. The team is divided into three groups that will be working on various systems: an underground heat exchanger, a rotating solar panel, and an insulation system.

The Science Technology and Society (STS) portion of the project involves trying to improve the appeal of net zero and other forms of more sustainable housing to the general public. This project will be done individually with guidance from Professor Catherine Baritaud from the University of Virginia's Engineering and Society department. Additional help for collecting resources will be given by University of Virginia librarian Maggie Nunley. The technical and STS portions of this project will be fairly tightly coupled as both deal with concepts related to sustainable and net zero housing; however, some divergence will take place as the STS portion of the project will focus less on the technologies of sustainable housing and more on how social and economic factors influence the implementation of such technologies. The technical portion of the project has 2 main deadlines: working scale models of each concept by the end of this semester and full implementation of each concept on a real house by the end of next semester.

The STS portion will be done by the end of next semester as a required fulfillment for graduation. Additional objectives are shown below in Figure 1.

Figure 1

Projected timeline of technical and STS projects

	Time									
objective	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Technical Project										
introduction										
form groups										
first presentation										
develop models										
design experiment										
write 1st semester report										
perform experiment										
build at full scale										
write final report										
STS Project										
Research Sources										
Write Procpectus										
Peer Review										
Edit Prospectus										
Write Final Thesis										

Note. From (Pazin, 2021)

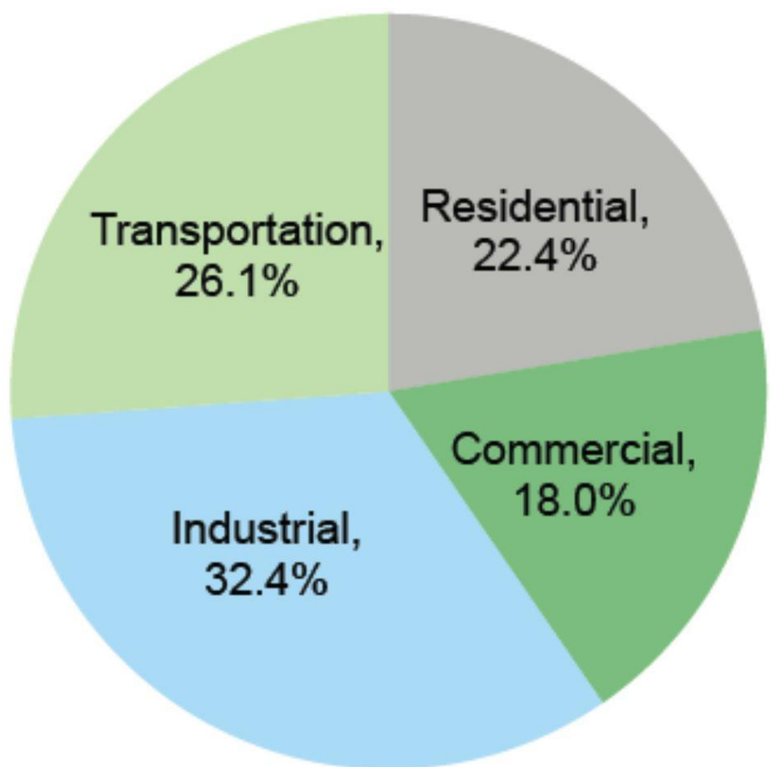
ENERGY CONSUMPTION OF CURRENT HOUSES

Housing and other buildings are currently large sources of energy consumption. Globally, the residential sector accounts for 25% of energy usage and 17% of greenhouse gas emissions

(Aram et al, 2020, para. 1). As seen in Figure 2, the United States' residential sector accounts for 22.4% of all energy consumption while residential daily consumption is 12.1 kilowatt-hours (kWh) per person (*U.S. Energy System Factsheet, 2021*, para. 2). Furthermore, the average American's energy consumption includes over 2 gallons of oil, almost 8 pounds of coal, and just over 250 cubic feet of natural gas (para. 2). The figures are also high in other parts of the world. For example, buildings also account for 36% of total carbon dioxide emissions in Europe (D'Agostino et al, 2020).

Figure 2

Energy usage by sector in the United States



Note. From (*U.S. ENERGY SYSTEM FACTSHEET*, 2021)

BUILDING A MORE SUSTAINABLE HOME

In order for a house to truly be considered net-zero, it must produce more energy than it consumes (Aaron et al, 2018). This is a difficult task and will likely require more work done beyond this year's capstone make a net-zero house. A home previously constructed in 2010 by the University of Virginia School of Architecture at the University of Virginia's Milton Airfield will be used as the basis for the project. A picture of the home is shown below in Figure 3. The insulation team's goal will be to design and apply a high performing and cost-effective insulation material or material combination to the walls and roof of the house to allow for significantly less energy to be consumed for heating and cooling the home. The goal for the heating and cooling team is to design and implement a heat exchanger that can be attached to a commercial ground source heat pump. The energy production team's goal is to design and implement a solar panel system that rotates to line up with the sun's rays and therefore allow each panel to produce more electricity.

Figure 3

Home designed by the University of Virginia School of Architecture

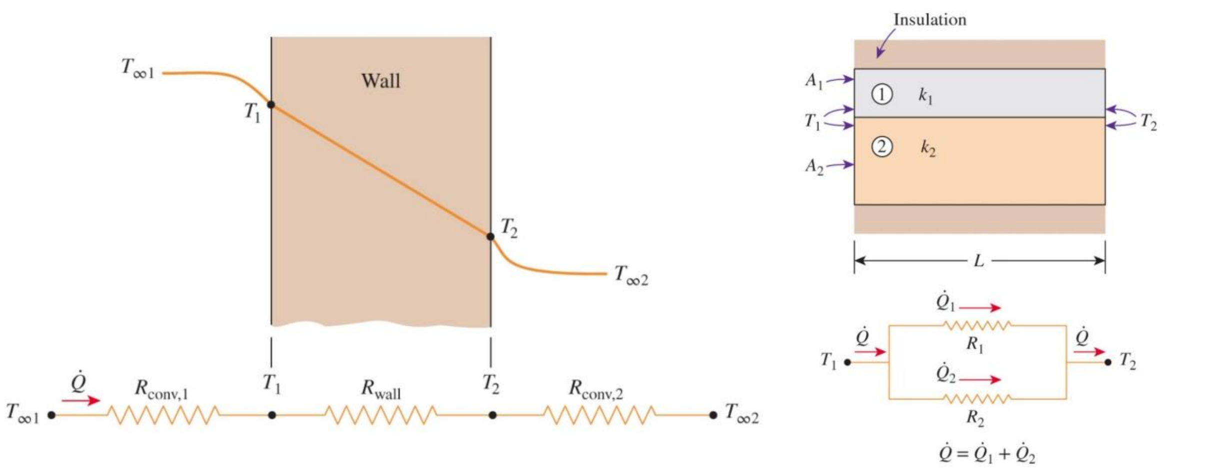
Note. From (Pazin, 2021)

An emphasis on the insulation team's progress will be applied in the technical section of this analysis. The insulation team has already done multiple sensitivity analyses to find which components contribute most to improving a home's insulation. When a one-dimensional heat transfer analysis was conducted (a sample diagram for a one-dimensional heat transfer analysis is shown in Figure 3), heat conduction through the insulation material was found to be the largest influence on insulation performance; although the model used for that analysis was relatively simple and had many simplifying assumptions. These assumptions include no leakage occurring, the pieces of insulation being modelled as infinitely large planes, the boundary conditions being treated as steady state, in other words, the inside and outside temperatures stayed constant, and that no forced convection, movement of gasses such as wind, took place. The one-dimensional heat transfer analysis involved the use of a thermal resistance network where each component was roughly treated similarly to how a resistor would be treated in an electrical circuit. Components in series with each other would have their resistances added together to contribute to the total resistance while components in parallel with each other would create a total thermal resistance that is the reciprocal of the sum of the reciprocals of the individual thermal resistance values of each component. In the equation, resistivity to convection is dependent on the surface area of the insulation, the thickness of the insulation, and the convection coefficient of the surrounding gas. When a literature review was done, it was found that gas conduction caused by leakage had the largest influence on insulation performance (Gangassaeter, 2017, p. 2). Causes of air leakage include the use of materials with large pores as well as poorly installed insulation (p. 2).

Once the one-dimensional heat transfer analysis is complete, presentations of these findings will be done. Next steps will include using SolidWorks to conduct heat transfer simulations of various insulation materials or material combinations already on the market. Other materials not currently used as insulation will also be tested if they appear to have promising properties. These potential insulation materials would be selected based on favorable properties such as low material costs, environmental friendliness, durability, and low thermal conductivities. Once this is completed, physical experiments will be conducted on the candidates that show the most promise in the SolidWorks simulations and one-dimensional heat transfer analyses. These physical experiments will most likely be done in the Experimental Methods Lab in the Mechanical and Aerospace Engineering building. Properties such as the rate of heat transfer will be measured when the insulation is set up in an area where the temperatures on each side will be kept constant but different from each other to satisfy the steady state assumption and therefore simplify any necessary calculations. The difference is important since no net heat transfer will take place if the temperatures on both sides of the insulation panel are the same (Ma, 2021, p. 8). Ideally, working models of the heat exchanger, rotating solar panel, and insulation systems will be complete before the end of the current semester while full scale implementations will be added to the house at the airfield by the end of the next semester. Professor Cheliah plans to continue adding future additions to the house with future classes in hopes of the house eventually meeting full net-zero criteria.

Figure 3

Parallel vs series thermal resistance networks



Note. From (Ma, 2021)

SUPPORT NEEDED FOR BUILDING A GREENER HOME

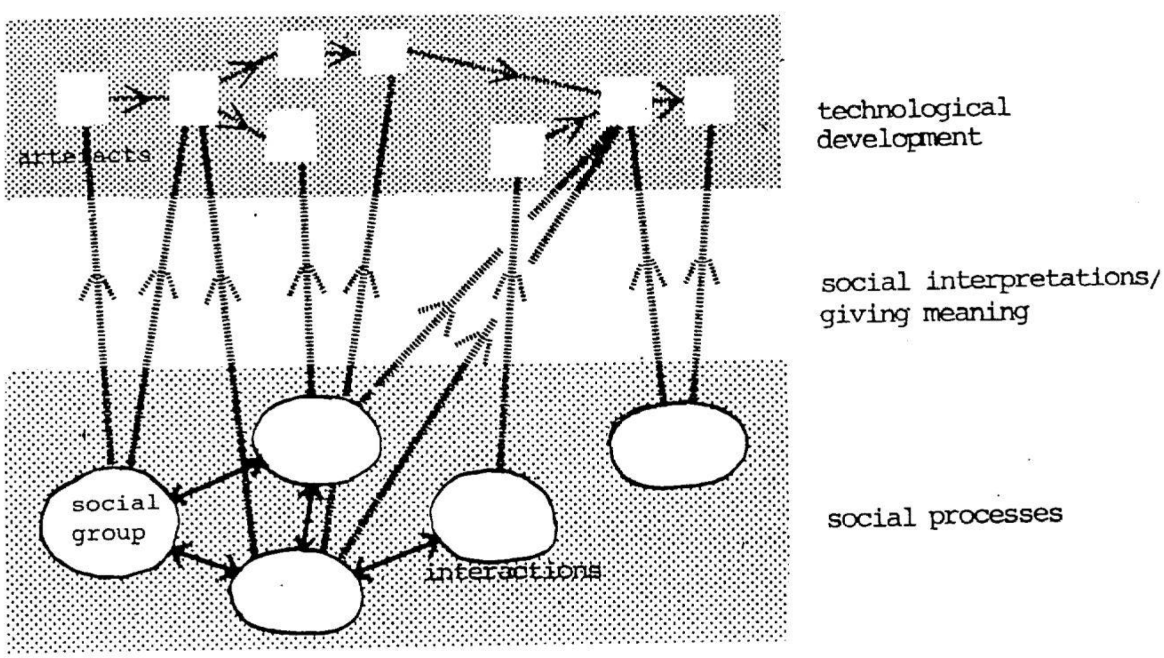
Applying for funding will be an ongoing process. Initially, $4000 will be given by the University of Virginia Mechanical and Aerospace Engineering department for each capstone class. The funds will be distributed among the three groups as a starting amount. However, more funding has been requested. About $8000 was requested to the University of Virginia Experiential Learning Fund to account for additional expenditures unable to be covered by the initial fund. Buying extra tubing, stepper motors, solar panels, and insulation materials are some of the items that should be covered by this fund. So far, the Experiential Learning Fund has not responded but should write back in early November. Lab equipment will be found in the Experimental Methods Laboratory, given by Professor Cheliah, or ordered online. The online ordering would most likely be done for smaller pieces of equipment such as insulation materials and thermocouples while the larger and more specialized equipment will be given. As building the physical components would likely start next semester, outside construction companies would likely need to be hired to help with the installation of components such as the below-ground heat exchanger since that would require the digging of large holes in the ground so the heat exchanger could be buried deep enough to keep its temperature moderated. Construction crews would likely need to be hired for the insulation since the use of power tools and personal protective equipment would be needed during the installation process. Funding for the second semester from the Experiential Learning Fund and other sources will be requested later but applications have not opened yet for these opportunities.

SOCIAL BARRIERS TO NET ZERO AND OTHER FORMS OF SUSTAINABLE HOUSING

Despite lots of technology currently on the market for making houses more energy efficient, many homes are still lagging in this metric. For example, 80% of homes in Australia were built before 2003 when energy efficiency regulations were established nationwide. Even since then, many homes built after that date have failed to meet those regulations (Amin et al, 2018, para. 2). Furthermore, homeowners likely know little about how well their homes stand up to the energy efficiency regulations currently in place (para. 2). Although work is being done to reduce the costs of net zero houses, net zero houses generally have higher upfront costs even if they result in long-term savings (Dowds & You, 2019, p. 5) (D'Agostino et al, 2020, para. 58) (Knuuti et al, 2017, p. 2) (Proskiw & Parekh, 2010, p. 1). In general, this problem does need more research on the technological and social side since although the upfront costs of sustainable housing have been reduced, they are still not feasible in colder climates (Knuuti et al, 2017, p. 1). The general approach for the STS portion of the project will be the use of Social Construction of Technology (SCOT) as seen in Figures 4 and 5. This was chosen since the lack of implementation of sustainable technologies in housing is at least partly due to people not valuing those technologies enough. This results in builders being more hesitant to add them into their developments (Lorinc, 2020, para. 37). Also, work toward decreasing the costs of such technologies is also influenced by this model since there is a social pressure to make sure products being sold are relatively affordable. The idea that social pressures influence technology applies enough in this scenario to make the SCOT model the best candidate for approaching why sustainable housing is not being implemented at a faster rate. The research question being answered is how can sustainable housing be more affordable and attractive. Some proposed solutions to the lack of sustainable housing include improving trust between homeowners and home renovation companies to allow for more upgrades to existing homes, the use of government incentives to cover the costs of sustainable technologies and changing the wording of various features to make them more enticing to customers (Lovell, 2007, para. 20) (Lorinc, 2020, para. 9) (de Wilde, 2019, p. 1). Another solution could be decreasing overall energy usage using systems that give feedback on energy usage (Inada et al, 2005, p. 1) or by encouraging people to buy smaller houses (Fuller et al, 2008, p. 5). In summary, many factors contribute to sustainable housing's relatively slow growth.

Figure 4

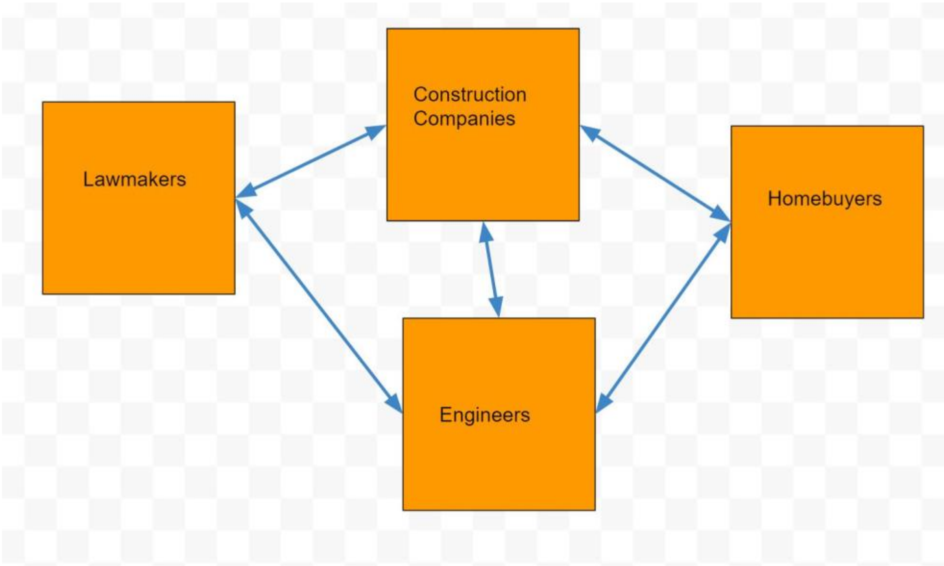
The basic idea of SCOT visualized



Note. From (Bijker et al, 1984)

Figure 5

SCOT applied to sustainable housing



Note. From (Pazin, 2021)

COMBINING SOCIAL AND TECHNOLOGICAL FACTORS TO IMPROVE NET ZERO HOUSING

In conclusion, technological and social factors will need to be considered in order for net zero housing to be implemented on a large scale. Technological factors include improving insulation, using ground source heat pumps, and the use of solar panels to minimize reliance on the power grid. A good first step to incentivize sustainable housing would be to reduce the cost of these technologies. However, the social side would need to be considered since hesitancy can stem from distrust in installation companies (de Wilde, 2019, p. 1) as well as people not seeing the benefits of sustainable technology in their homes. In conclusion, net zero housing needs to be considered from a technological, social, and economic standpoint.

REFERENCES

Aaron, L., L., Amin, Z., Gray, M., Miller, W. (2018). Involving occupants in net-zero-energy solar housing retrofits: An Australian sub-tropical case study, *Solar energy*, 159, 390-404. https://doi.org/10.1016/jsolener.2017.10.008

Ashjaee, M., Eshraghi, J., Khosroshahi, S., S., Mirkhani, N., & Narjabadifam, N. (2014). A comprehensive feasibility study of applying solar energy to design a zero energy building for a typical home in Tehran, *Energy and Buildings,* 72, 329-339, https://doi.org/10.1016/j.enbuild.2014.01.001

Bijker, V. W., Bonig, J., & van Oost, E. (1984). The Social Construction of Technological Artefacts [Figure 4]. *Zeitschrift Für Wissenschaftsforschung : Interdisziplinäres Organ Für Philosophische Wissenschaftsforschung = Journal for Science Research*, *3*, 39–51.

Center for Sustainable Systems, University of Michigan. 2021. "U.S. Energy System Factsheet." Pub. No. CSS03-11.

D'Agostino, D., Mele, L., Minichiello, F., & Renno, C. (2020). The use of ground source heat pump to achieve a net zero energy building. *Energies*, *13*(13), 3450. https://doi.org/10.3390/en13133450

Dowds, M. & You, S. (2019). Economic analysis of the routes for fulfilment of net-zero energy buildings (NZEBs) in the UK. *Energy Procedia*, 158, https://reader.elsevier.com/reader/sd/pii/S1876610219309580?token=4969965645401B5DC8D74E251467405407967BF45ACA44C6645EB1DF1F6C124A65E0581783CCA87E5303402C3668D043&originRegion=us-east-1&originCreation=20211005022111

Fuller, R., de Jong, U., Mellersh-Lucas, S. (2008). The Ethics of Sustainable Housing Design:

The Dilemma for Practising Architects. *Architectural Science Review*, 51(3), 231-238, https://doi.org/10.3763/asre.2008.5128

Gangassaeter, et al. (2017). “Air-Filled Nanopore Based High-Performance Thermal Insulation Materials.” *Energy Procedia*, Vol. 132, 231-236. https://doi.org/10.1016/j.egypro.2017.09.760

Inada, T., Saeki, O., Tsuji, K., & Ueno, T. (2005). Effectiveness of displaying energy consumption data in residential houses Analysis on how the residents respond. *European Council for an Energy Efficient Economy*, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.391.7417&rep=rep1&type=pdf

Khakian, R., Karimimoshaver, M., Aram, F., Zoroufchi Benis, S., Mosavi, A., & Varkonyi-Koczy, A. R. (2020). Modeling nearly zero energy buildings for sustainable development in rural areas. *Energies*, *13*(10), 2593. https://doi.org/10.3390/en13102593

Knuuti, A., Paiho, S., & Pulakka, S. (2017). Life-cycle cost analyses of heat pump concepts for Finnish new nearly zero energy residential buildings. *Energy and Buildings*, 150, 396-402. https://doi.org/10.1016/j.enbuild.2017.06.034

Lorinc, J. (2021, August 27). *The case for funding more affordable green housing*. Corporate Knights. Retrieved September 23, 2021, from https://www.corporateknights.com/built-environment/case-funding-affordable-green-housing/.

Lovell, H. (2007). Framing sustainable housing as a solution to climate change, *Journal of Environmental Policy & Planning*, 6(1), 35-55, https://doi.org/10.1080/1523908042000259677

Ma, L. (2021). *Parallel vs series thermal resistance networks* [Figure 2]. *Heat Transfer* (Unpublished). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Pazin, J. (2021). *Projected timeline of technical and STS projects* [Figure 1]. Prospectus

(Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Pazin, J. (2021). *Home designed by the University of Virginia School of Architecture* [Figure 3]. Prospectus (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Pazin, J. (2021). *SCOT applied to sustainable housing* [Figure 5]. Prospectus (Unpublished undergraduate thesis). School of Engineering and Applied Science, University of Virginia. Charlottesville, VA.

Proskiw, G. & Parekh, A. (2010). Optimization of Net Zero Energy Houses. *Energy Efficiency,* 3 (3), https://www.greenbuildingadvisor.com/app/uploads/sites/default/files/Optimization%20Of%20Net%20Zero%20Energy%20Houses.pdf

de Wilde, M. (2019). The sustainable housing question: On the role of interpersonal, impersonal and professional trust in low-carbon retrofit decisions by homeowners, *Energy Research & Social Science,* 51, 138-147, https://doi.org/10.1016/j.erss.2019.01.004