Towards net-zero energy: Lessons for architectural design education

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ABSTRACT: This paper explores the goals, methods, and lessons from six years of teaching a required graduate course focusing on the integration of luminous and thermal design for net-zero energy architecture. An integrated approach to passive heating, natural ventilation, and daylighting were at the core of this design curriculum, into which innovative systems and renewable energy were integrated. Design excellence, comfort, and human experience were of equal importance as energy and ecological performance. The goal of the course was to foster student awareness, intuition, and design skills to support qualitative and quantitative decision making in the early phases of low- and net-zero energy architectural design. The objective of this paper is to share the teaching and learning goals, net-zero energy design protocols, and assessment methodologies. Concluding lessons for design educators will address pedagogical consideration for developing a net-zero energy architecture curriculum.

KEYWORDS: Net-zero Energy, Architectural Education, Energy Modeling, Passive Solar Design

INTRODUCTION

The aspiration for net-zero (and increasingly net-positive) energy architecture is generating an evolution in the design professions and a transformation in architectural education. To prepare students for the energy and ecological challenges of our day, net-zero energy is a now a foundational topic for design studio and related topical courses. To meet these pressing professional needs, the School of Architecture at the University of Minnesota has explored and tested three distinct models for teaching a required net-zero design curriculum for the first year graduate students in the professional M.Arch program. The paper will discuss educational goals, metrics, design protocols, and student outcomes. Concluding lessons will address pedagogical consideration for developing courses for net-zero design education. (In the following sections the term “net-zero energy” will be used; however the author acknowledges the critical shift to “net-positive energy” architecture which produces on an annual basis more energy than it consumes.)

Research by the US Green Building Council (USGBC) confirms this trend: *“While ZNE [zero-net energy] buildings currently make up a very small fraction of the overall green building market today, it’s clear that this new frontier in sustainability is gaining traction”* (Dorn, USGBC). The New Building Institute’s (NBI’s) *2014 Getting to Zero Status Update* studied 160 buildings constructed since 2012 and concludes*:*

> Zero net energy (ZNE) buildings have captivated the minds of leading design firms, companies, schools, foundations and governments that are showing the way to a lower-carbon future. In just a few years ZNE has transitioned from an impossible concept to a quite probable future. ZNE buildings have now moved beyond a handful of small demonstration projects by universities or nonprofits to more widely mainstream building types and sizes. (NBI, 1, 10).

To meet every higher levels of energy performance, both the USGBC and the NBI underscore the need to explore new approaches to programming, architectural design, technology, systems, and operations (USGBC, NBI). To reach these new levels of energy performance, architects are integrating ancient lessons of passive and climate-responsive design with state-of-the art technologies and new, innovative approaches to high-performance and responsive building envelopes.

1.0 NET-ZERO DESIGN EDUCATION

The ability to define fundamental energy-consumption and sustainable performance metrics, strategies, and assessment methods is often lacking in both the academy and practice, at the same time as the shifting aspiration from net-zero to net-positive energy design continues to raise the bar. The need for clearly articulated performance criteria, metrics, and assessment protocols to measure design outcomes is identified as the first of four research priorities and trends in the *AIA Sustainability Leadership Opportunity Scan*:

> **#1: Drive for measured performance:** The global design and construction industry is transitioning from loose, aspirational sustainable goals to measured performance expectations and requirements. Optional rating systems (such as LEED) helped set the stage for this approach, but requirements are expanding to include actual performance and measured design outcomes (AIA 2013, 7).

While the profession and the academy are grappling with the complexity of defining metrics, there is also the challenge of defining effective teaching methods and protocols. In 2006, the *Architecture 2030 Challenge* made the call to the profession and educational institutions for incremental shifts to “carbon-neutral design by the year 2030” and launched the *2010 Imperative* “Global Teach-in” in 2007. For accredited programs of architecture, the first reference to “carbon-neutral design” (and indirectly net-zero energy) appeared in the

2009 Conditions for Accreditation by the *National Architectural Accreditation Board* (NAAB). Yet despite the 2009 trajectory to integrate net-zero and carbon-neutral design into architectural education, NAAB's *2014 Conditions for Accreditation* have recently removed the criterion for "Sustainability" and replaced it with "Integrative Design." The new criterion eliminates *"carbon-neutral design*" (and indirectly net-zero energy) to be replaced by the less energy-specific description *"environmental stewardship"* (NAAB, 2014, 18-19). Please see Table 1 for related criteria from the *2009 and 2014 Conditions for Accreditation*.

Table 1: NAAB Conditions for Accreditation 2009 and 2014 (NAAB 2009, 24-25 and NAAB 2013, 18-19).

NAAB 2009 Conditions for Accreditation July 2009:	**NAAB 2014 Conditions for Accreditation, First Draft August 2013**
B. 3. Sustainability: *Ability* to design projects that optimize, conserve, or reuse natural and built resources, provide healthful environments for occupants/users, and reduce the environmental impacts of building construction and operations on future generations through means such as carbon-neutral design, bioclimatic design, and energy efficiency.	**Integrative Design**: *Ability* to produce an architectural solution that demonstrates the ability to make design decisions about a single project while demonstrating broad integration and consideration of environmental stewardship, technical documentation, accessibility, site conditions, life safety, environmental systems, structural systems, and building envelope systems and assemblies.
B. 8 Environmental Systems: *Understanding* the principles of environmental systems' design such as embodied energy, active and passive heating and cooling, indoor air quality, solar orientation, daylighting and artificial illumination, and acoustics; including the use of appropriate performance assessment tools.	**B.6 Environmental Systems:** *Understanding* the principles of environmental systems' design, which must include active and passive heating and cooling, indoor air quality, solar orientation, daylighting and artificial illumination, and acoustics; and an understanding of performance assessment tools.

While there is a great desire to teach net-zero design, practical teaching methods and tools are still in the nascent stage. There are no clear pedagogical directives or organized approaches by the *Associate Collegiate Schools of Architecture* (ACSA), the *National Council of Architectural Registration Boards* (NCARB), or the *National Architectural Accrediting Board* (NAAB). For educators trying to develop a curriculum using emerging definitions and protocols, institutional support from ACSA and NAAB are essential in leveraging from administrators the necessary time and funding to develop teaching resources.

2.0. A CURRICULUM RESPONSE FOR NET-ZERO DESIGN

The School of Architecture at the University of Minnesota has explored three approaches since 2008 to integrating net-zero design education into the professional M.Arch program. The required graduate-level course focused on the integration of luminous and thermal design strategies and technologies to eliminate fossil fuel energy consumption in building operations for heating, lighting, and cooling. An integrated approach to passive heating, natural ventilation, and daylighting were at the core of this design curriculum, into which innovative systems and renewable energy were integrated. Design excellence, comfort, and human experience were given importance equal to energy and ecological performance. The desired outcome of the course was to foster student awareness, design skills, and intuition to support qualitative and quantitative decision making in the early phases of programming and schematic design of low- and net-zero energy architectural design. The following discussion outlines the curriculum development process over the past six years.

2.1. Assemble a net-zero teaching cohort

Given the complexity and emerging nature of the topic, the School has reached out to energy experts and sustainable design researchers to help develop and teach net-zero design strategies and methods. It was essential to assemble a faculty cohort with expertise in both net-zero design in professional practice as well as curriculum development and teaching. The faculty cohort was structured to include either a full-time faculty member or a full-time research practitioner responsible for curriculum oversight and coordination and two part-time adjunct faculty from practice with expertise in energy and/or digital assessment methods and tools. Despite innovative regional guidelines and design resources for the *Minnesota Sustainable Design Guide* as well as the *State of Minnesota Energy Design Assistance Program*, there are few local and regional professionals who have expertise in net-zero design in the early design phases. One of several goals of the net-zero curriculum is to enable students to enter the profession with viable and transferrable early net-zero energy design knowledge and skills.

2.2. Clarify net-zero educational goals

Although the course has been taught in various formats, the goals have remained consistent: 1) Promote ecological and holistic systems thinking, 2) Explore formal, aesthetic and experiential design opportunities, 3) Integrate appropriate design and technology applications, and 4) Develop methods of design and performance assessment and testing. As a required course for the graduate cohort designated to meet the level of "ability" specified in the *NAAB Criterion: B3: Sustainability*, it was essential that tangible design strategies, assessment methods and tools be introduced and actively applied to design by the students *("…'ability' to design projects that optimize, conserve, or reuse natural and built resources …through means such as carbon-neutral design, bioclimatic design, and energy efficiency,"* NAAB, 2009). Passive design and its role in reducing energy consumption in cold-climate architecture were at the heart of the curriculum.

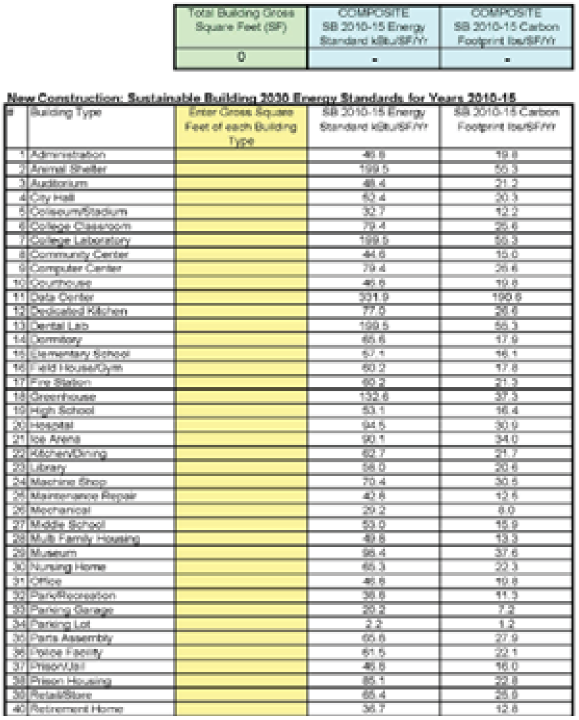
2.3. Define net-zero design curriculum format

A significant structural challenge was how to include in an already dense curriculum the additional time and expertise essential to develop, test, and implement a net-positive energy curriculum. During the past six years, the net-zero energy course has been taught in three formats: 1) two 3-credit, 15-week parallel technology lecture courses, 2) a 6-credit, 7-week hybrid lecture course and technology studio, and 3) and a 9-credit, 15-week ecological comprehensive design studio. In all of the course formats, the students moved through a series of exercises taking net-zero thermal and luminous energy design from the site to building, envelope, and systems scales. The net-zero design and assessment protocol for the course includes four steps and a sequence of related assignments: 1) set project goals, 2) minimize loads, 3) meet energy loads, and 4) use renewable sources (a detailed discussion is provided below in *Section 3.0: A Net-Zero Design Protocol*).

2.4. Assess net-zero teaching resources

Evaluating and building upon existing teaching resources and tools is essential given the emerging nature of net-zero design. Useful resources include the *Carbon Neutral Design Project* and the *2030 Palette*. To provide support for design educators, the *Society of Building Science Educators and AIA* have created the *Carbon-Neutral Design Project* to share teaching resources across schools of architecture in North America (SBSE, 2010). With twenty-six faculty form schools of architecture participating in the project by sharing syllabi, course assignments, toolkits, and assessment methods, the website includes an excellent cross-section of curricular approaches. Additional funding is needed to keep the effort updated with the most current teaching methods and outcomes. An alternate resource is provided by *Architecture 2030*, which launched the *2030 Palette* to provide design strategies and case-studies. Although not a design or assessment tool, the *2030 Palette* provides *"The principles and actions needed to create low-carbon and resilient built environments worldwide,"* including excellent case studies, strategy guidelines, rules-of-thumb, and resources across scales, topical areas, and climate (Architecture 2030).

While these and related resources are extremely useful for design education, there is an urgent need for user-friendly design protocols and tools in the early schematic design phase to enable students (and practitioners) to easily and quickly compare design strategies and trade-offs. Learning, evaluating, and integrating the most effective assessment tools requires time and expertise, given the diversity of early design tools such as *Sefaira Concept* and more robust assessment tools such as *Integrated Environmental Solutions Virtual Environment* (IES VE Pro). Several assessment tools were used in the first six years in the course, including *Ecotect, Diva*; *IES VE*, and *Sefaira Concept*. While the most effective program for design integration for thermal, luminous, and systems was found to be *IES VE*. Since tools are under continuous development, students are taught to master design protocols and assessment methods rather than a specific tool.



Total Building Gross Square Feet (SF)	COMPOSITE SB 2010-15 Energy Standard kBtu/SF/Yr	COMPOSITE SB 2010-15 Carbon Footprint lbs/SF/Yr
0	-	-

New Construction: Sustainable Building 2030 Energy Standards for Years 2010-15

#	Building Type	Enter Gross Square Feet of each Building Type	SB 2010-15 Energy Standard kBtu/SF/Yr	SB 2010-15 Carbon Footprint lbs/SF/Yr
1	Administration		46.8	19.8
2	Animal Shelter		199.5	55.3
3	Auditorium		48.4	21.2
4	City Hall		50.4	20.3
5	Coliseum/Stadium		32.7	12.2
6	College Classroom		79.4	25.6
7	College Laboratory		199.5	55.3
8	Community Center		44.6	15.0
9	Computer Center		79.4	25.6
10	Courthouse		46.8	19.8
11	Data Center		331.9	190.6
12	Dedicated Kitchen		77.0	28.6
13	Dental Lab		199.5	55.3
14	Dormitory		65.6	17.9
15	Elementary School		57.1	16.1
16	Field House/Gym		60.2	17.8
17	Fire Station		60.2	21.3
18	Greenhouse		132.6	37.3
19	High School		53.1	16.4
20	Hospital		94.5	30.9
21	Ice Arena		90.1	34.0
22	Kitchen/Dining		62.7	21.7
23	Library		58.0	20.6
24	Machine Shop		70.4	30.5
25	Maintenance Repair		42.8	12.5
26	Mechanical		29.2	8.0
27	Middle School		53.0	15.9
28	Multi Family Housing		49.8	13.3
29	Museum		98.4	37.6
30	Nursing Home		65.3	22.3
31	Office		46.8	19.8
32	Park/Recreation		38.8	11.3
33	Parking Garage		20.2	7.2
34	Parking Lot		2.2	1.2
35	Parts Assembly		65.8	27.9
36	Police Facility		61.5	22.1
37	Prison/Jail		46.8	16.0
38	Prison Housing		85.1	22.8
39	Retail/Store		65.4	25.9
40	Retirement Home		36.7	12.8

Figure 1: SB2030 Energy Worksheet is used to define the 2030 Baseline for the given year. Source: (SB2030, 2014).

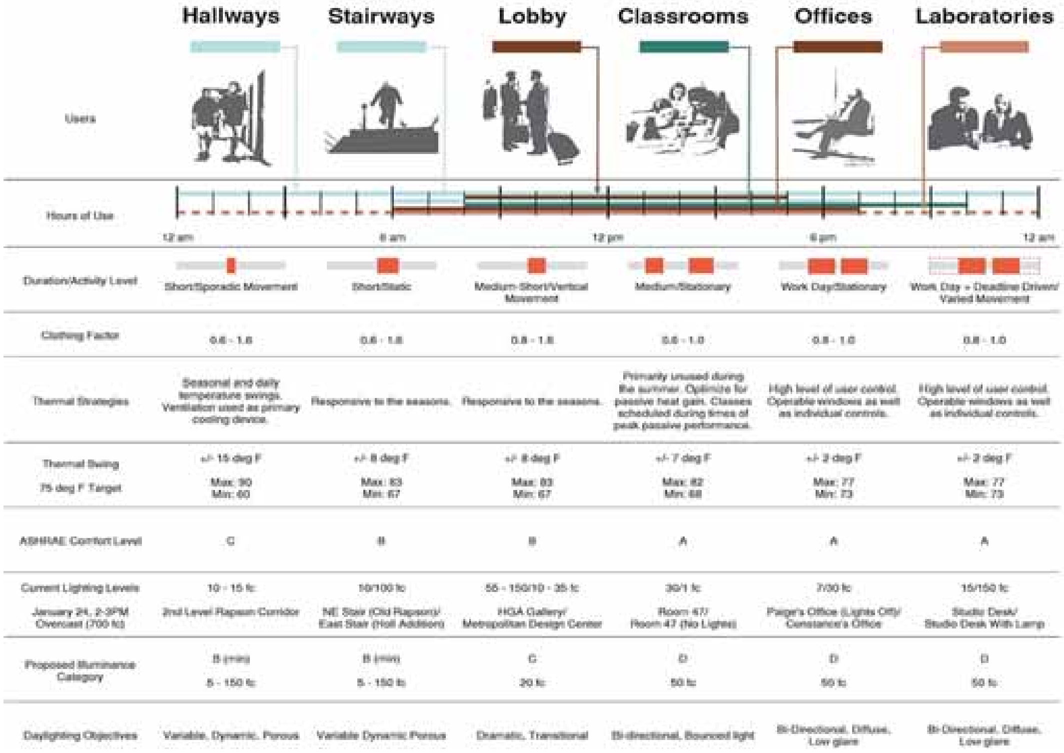
2.5. Develop, test and revise curriculum

Over the past six years, the faculty cohort has worked with Dr. Ilene Alexander from the Center for Teaching and Learning Services (CTLS) to develop the course, conduct mid-course evaluations, and to critique the course effectiveness. The partnership with CTLS has been essential in having an objective assessment of the strengths and weakness of the curriculum and in focusing efforts to improve the course.

3.0. A NET-ZERO DESIGN PROTOCOL FOR ARCHITECTURAL EDUCATION

3.1. Set project energy goals: define baseline and programming opportunities

The *Architecture 2030 Challenge* goal of incremental steps toward "carbon-neutrality" is used as the "energy and carbon baseline" from which students develop design strategies to reduce energy toward "net-zero and beyond." The *State of Minnesota Sustainable Building Guideline's SB2030 Energy Standard Worksheet for New Construction* (SB2030) is used to define the baseline energy and carbon benchmark for the *Architecture 2030* incremental carbon-reduction target for the given year, building type, program activities, and square footage. The *SB2030 Worksheet* has the advantage of being tailored to regional building energy codes and a cold-climate building energy database. This baseline provides the current-day energy requirements to meet the *Architecture 2030* incremental target, for example in 2014, buildings have to meet 60% energy and carbon reductions from an average building for a given program, locale and climate. The baseline metrics are used to compare design strategies over the development of the project, using the *Energy Standard in kbu/SF/Yr* and the related *Carbon Footprint in lbs/SF/Yr* (*SB2030 Worksheet*: http://sb2030.twgidemo.com/SB2030Calculator/.). In addition to quantitative benchmarks, students are asked to develop a "luminous and thermal program" exploring the qualitative and experiential dimensions of net-zero design and programming opportunities for energy and carbon reduction. The "luminous and thermal program" provides an opportunity for students to weigh the balance of energy targets with thermal and luminous comfort as well as the desired seasonal qualities and atmosphere of the architectural spaces (Figure 2).



	Hallways	Stairways	Lobby	Classrooms	Offices	Laboratories
Duration/Activity Level	Short/Sporadic Movement	Short/Static	Medium-Short/Vertical Movement	Medium/Stationary	Work Day/Stationary	Work Day + Deadline Driven/ Varied Movement
Clothing Factor	0.6 - 1.6	0.6 - 1.6	0.8 - 1.6	0.6 - 1.0	0.8 - 1.0	0.8 - 1.0
Thermal Strategies	Seasonal and daily temperature swings. Ventilation used as primary cooling device.	Responsive to the seasons.	Responsive to the seasons.	Primarily unused during the summer. Optimize for passive heat gain. Classes scheduled during times of peak passive performance.	High level of user control. Operable windows as well as individual controls.	High level of user control. Operable windows as well as individual controls.
Thermal Swing 75 deg F Target	+/- 15 deg F Max: 90 Min: 60	+/- 8 deg F Max: 83 Min: 67	+/- 8 deg F Max: 83 Min: 67	+/- 7 deg F Max: 82 Min: 68	+/- 2 deg F Max: 77 Min: 73	+/- 2 deg F Max: 77 Min: 73
ASHRAE Comfort Level	C	B	B	A	A	A
Current Lighting Levels January 24, 2-3PM Overcast (700 fc)	10 - 15 fc 2nd Level Rapson Corridor	10/100 fc NE Stair (Old Rapson)/ East Stair (Holl Addition)	55 - 150/10 - 35 fc HGA Gallery/ Metropolitan Design Center	30/1 fc Room 47/ Room 47 (No Lights)	7/30 fc Paige's Office (Lights Off)/ Constance's Office	15/150 fc Studio Desk/ Studio Desk With Lamp
Proposed Illuminance Category	B (min) 5 - 150 fc	B (min) 5 - 150 fc	C 20 fc	D 50 fc	D 50 fc	D 50 fc
Daylighting Objectives	Variable, Dynamic, Porous	Variable Dynamic Porous	Dramatic, Transitional	Bi-directional, Bounced light	Bi-Directional, Diffuse, Low glare	Bi-Directional, Diffuse, Low glare

Figure 2: Example Daylight and Thermal Program (Anton, Bussey, Green, Ennon). Source: (Abraham/Weber, 2013).

3.2. Minimize loads: passive priority

Using the *Architecture 2030* energy and carbon performance metrics as a baseline, students are then asked to investigate, through design testing and parametric analyses of daylighting, thermal, and energy, how much they can reduce energy consumption from "today's *Architecture 2030* target" while maintaining visual and thermal comfort and design excellence. Students begin by minimizing loads through the use of "architectural strategies" such as passive solar heating, natural ventilation, and daylighting, space use, and programming. Working in teams, they use a sequence of exercises that investigate site and bioclimatic forces to develop three architectural proposals shaped by daylight, passive heating, and natural ventilation.

The design projects have varied from a 20,000 square-foot "Zero Energy Lab" to a 40,000 square foot "Student Health Center" on the University campus. The initial design and performance goal is not necessarily to achieve "net-zero or beyond," but to understand how architectural design, passive strategies, comfort, and energy decisions are interrelated. Students are introduced right away to design assessment methods and tools that evaluate the total annual energy use and carbon emissions for each of the three design proposals. In addition to daylighting and thermal analyses using *IES VE*, teams develop design proposals using physical models, traditional drawings, and diagrams. Based on the three architectural proposals, students are asked to critique the designs in comparison to the "SB2030 baseline" for energy and carbon performance as well as daylighting and thermal comfort, considering: 1) Were they able to reduce energy consumption and carbon emissions through passive strategies, architectural design interventions, and systems interventions, 2) What trade-offs and poetic, practical, and programmatic priorities influenced design decisions, 3) What level of energy and carbon performance were met and how did they determine “how low they could go”, and 4) What strategies made the greatest impact on energy and emission while supporting overall design excellence (Figure 3).

Figure 3: Baseline and Passive Design Comparison (Abin-Fluentes, Raznik, Triggs). Source: (Abraham/Weber, 2013).

3.3. Meet energy loads: optimizing envelope and whole building design

After assessing the “passive potential” for reducing energy loads, students explore a series of exercises that help them meet the remaining energy loads using high performance envelope design integrated with heating, cooling, lighting systems. Parametric energy studies are used to explore how the design of the building envelope can be used to optimize energy performance by changing design variables such as wall construction, glazing type, insulation, window size and configuration, orientation, and shading and solar control. Each student on the team defines a “thermal hypothesis” to test through parametric analysis; for example, *“Hypothesis 1: The orientation of the window does not affect energy performance in a building over 20,000 square feet in this local cold climate; “Hypothesis 2: Roof insulation is the most important construction factor for energy performance and thermal comfort; “Hypothesis 3: Daylighting can be integrated with passive solar to meet seasonal lighting and cooling loads without compromising visual and thermal comfort.”* Students then conduct parametric analyses to incrementally reduce energy and optimize performance and comfort (Figure 4). Physical models and annotated drawings complement the quantitative assessment to illustrate broader aesthetic and experiential design concepts.

A series of “whole building design revisions” are then developed to assess how the envelope and construction details influence annual energy loads and carbon emissions. Thermal and visual comfort studies illustrate the percentage of satisfied occupants while annual monthly heating and cooling loads for each “whole building design revision” are compared to the *SB2030 Baseline* for energy loads and carbon emissions (Figure 5). In addition to energy and comfort studies, students use more traditional drawings, physical models, and diagramming to explore overall architectural design concepts. At this mid-way point in the design exploration, students have gained confidence in working with IES VE as a “design tool” for daylighting, thermal, and comfort analyses. The “whole building assessment” is followed by studies of “one important room” using a sequence of physical models to assess the quality of daylighting and thermal comfort through the seasons. Time-sequence photographs of physical day-lighting models are used to investigate the relationship between the luminous quality and visual and thermal comfort. Parallel seasonal illuminance studies, daylight autonomy, and thermal comfort analyses complement the qualitative physical model studies. These experiential studies are a springboard to the final renewable and mechanical systems integration and design synthesis (Figure 6).

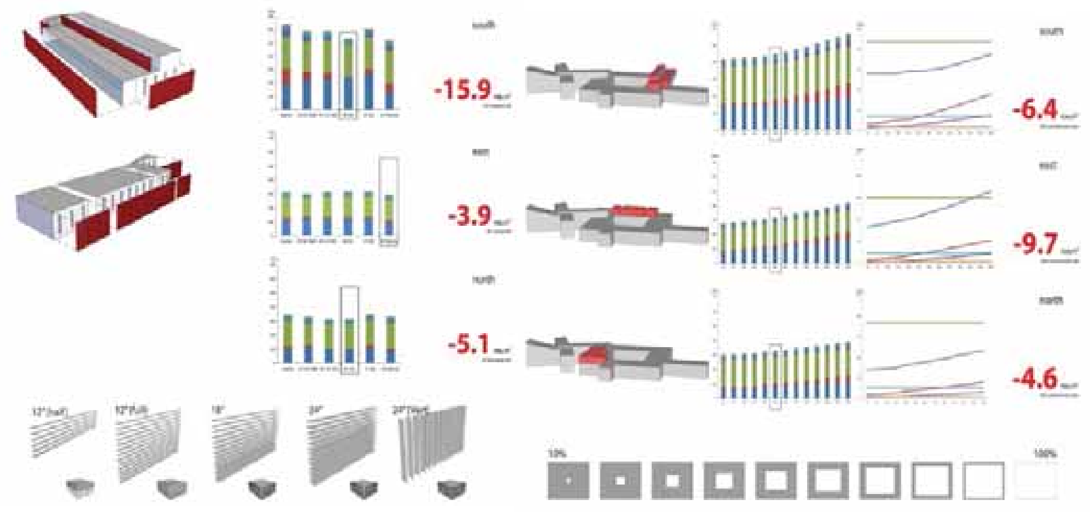


Figure 4: Envelope Optimization (Deveau, Koslovski, Partridge, Salehashafa). Source: (Abraham/Guzowski 2014).

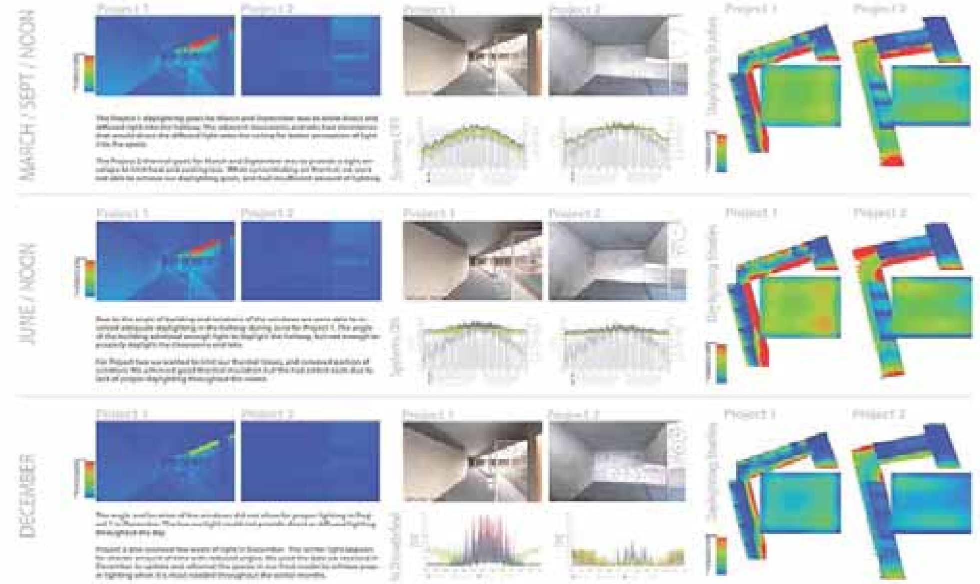


Figure 5: Daylighting and Thermal Comfort Optimization (Kopp, Hourey, Daley, Ghanbari). Source: (Abraham/Guzowski 2014).

3.4. Use renewable energy and non-fossil fuel sources: systems integration and synthesis

The final phase of the design exploration considers the integration of appropriate renewable energy and fuel sources, including solar thermal, photovoltaic, geothermal, and wind. Students are asked to use the qualitative and quantitative design methods and tools to develop a final net-zero design proposal integrating daylighting, thermal comfort, energy, and carbon emissions. In order to estimate and compare the total energy consumption and carbon emissions, students are provided with a carbon calculator. During the past several years the course has used the *Zero+ Calculator* tailored to the climate, building program, and square footage (developed with research funding from the University of Minnesota). The *Zero+ Calculator* is an

Excel-based spreadsheet that allows for the aggregation and integration of simulation results from IES VE into a set of graphs to illustrate the integrated energy performance and carbon footprint.

Final projects are presented using physical massing and detail models, traditional design drawings (plans, sections, elevations), diagrams, experiential images (renderings and daylight model photographs), and final quantitative analysis of the energy performance and carbon emissions *(Energy Consumption in kbu/SF/Yr* and *Carbon Footprint in lbs/SF/Yr).* Teams are asked to critique the final proposal using the following questions: 1) *Design Intentions, Concepts, and Strategies*: Summarize the critical design intentions, concepts, and strategies related to daylight, thermal, and zero-energy design, 2) *Net-zero Energy Performance*: State clearly how well your final design meets your net-zero energy performance goal using written and graphic means, 3) *Carbon Emissions*: State clearly how well your final design performs in terms of annual carbon emissions using written and graphic means, 4) *Ecological Impacts/Benefits*: Summarize the ecological benefits of your final design to the community and surrounding eco-systems; and 5) *Strengths, Trade-offs, and Lessons*: Critique the final design decisions, priorities, and trade-offs (Figure 6). For detailed syllabi, exercises, and information on the design outcomes of the student projects, please see the *Zero+ Campus Design Project:* http://zeropluscampus.umn.edu/courses/thermalandluminous.php.

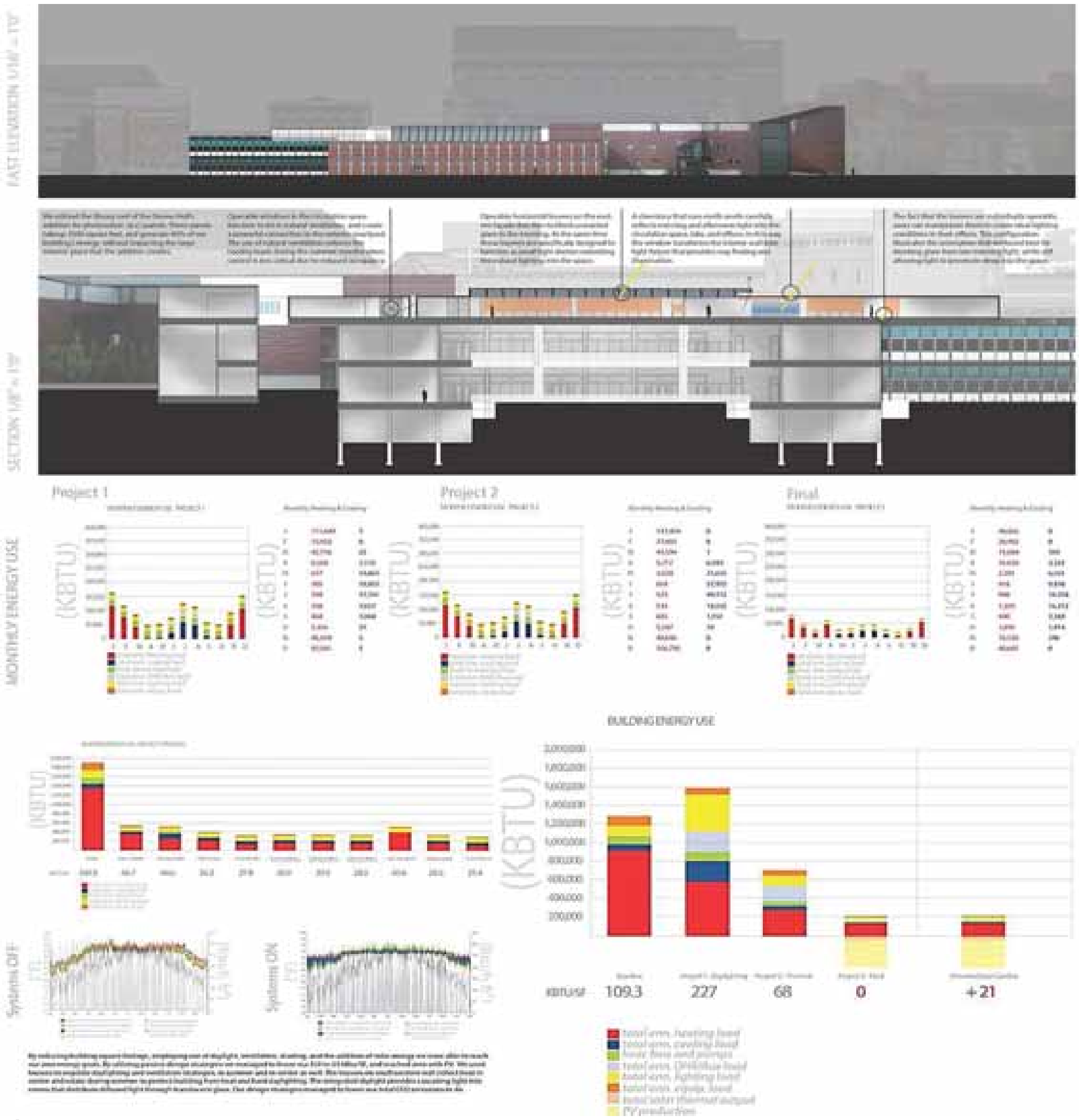


Figure 6: Whole building analysis compared to baseline (Kopp, Houri, Daley, Ghanbari). Source: (Abraham/Guzowski 2014).

CONCLUSION

This net-zero architecture course asks students to explore the relationships between luminous and thermal design and to consider a fresh perspective on the roles of "passive design" and "solar architecture" in reaching net-zero energy in cold-climate architecture. Net-zero design protocols integrate essential solar principles and precepts (such as attention to building orientation, appropriate room depth and height, methods of solar control, effective material characteristics and colors, and responses to seasonal change); state-of-the art technologies, and innovative approaches to building programming and use. The integration of poetic and pragmatic considerations is a distinguishing feature of the most innovative and elegant design approaches to net-zero energy and carbon-neutral architecture; revealing that it is possible (and necessary) to respond to urgent ecological challenges with beautiful and meaningful architectural experiences. Students are encouraged to consider how net-zero architectural expressions are diverse and open to creative interpretation. As Architect and sustainable design expert Mario Cucinella argues, energy and carbon are at the heart of good design: "*There is an aesthetic in carbon-neutral design, in beautiful buildings. The future of sustainable design is not about more photovoltaics. In the future of building, we need more work on the quality of space and integration of solar and carbon-neutral design so that it is part of the process—so that the shape of the building solves the problem"* (Guzowski, 191).

Nearly a decade after the *Architecture 2030 Challenge* was launched, high-performance design strategies and mechanical systems have enable practitioners to meet today's targeted fossil-fuel reductions of 60%. Achieving the remaining 70-100% reductions will require new ways of approaching architectural design, passive and bioclimatic strategies, programming, and occupancy that go beyond our current models of energy efficiency and systems integration. The following suggestions distilled from the course should be helpful for those considering development of a net-zero design curriculum:

1. *Establish partnerships between practice, research, and the academy:* Diverse expertise is needed to design a net-zero curriculum, including energy and technical expertise as well as experience in curriculum development. Given the complexity of the issues and design methods, it is essential to establish a faculty cohort with complementary strengths in practice, research, and teaching.
2. *Foster administrative awareness and support:* A demonstrable and sustained commitment is needed to develop, test, and refine a net-zero curriculum. Take time to educate administrators about the challenges and opportunities of creating a curriculum in this emerging area. Dedicated resources and time will be needed to assess existing resources, master new tools, and develop resources and tutorials for students. Given their evolving nature, sustained support is particularly needed for computer tutorials and digital resources.
3. *Relax with creating the path as you go*: Acknowledge that there is a lack of clarity in the design education community regarding common net-zero goals, metrics, and protocols. Invite students into the dialogue and foster an atmosphere of curiosity and exploration, while acknowledging the emerging nature of the topic.
4. *Teaching and learning a process*: Emphasize the value of learning iterative and parametric design processes and methods that enable designers to balance quantitative performance goals with qualitative and experiential design intentions. Students weigh their individual design priorities and ecological values as they reconcile the project goals and energy performance with potential design strategies and trade-offs.

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