The Life and Death of a Solar Energy Course – Lessons in Challenge Based Learning

Nelson Sommerfeldt

KTH Royal Institute of Technology, Stockholm (Sweden)

Abstract

This paper presents the experiences of developing and executing a graduate solar energy engineering course designed around challenge based learning (CBL). The course structure is presented and mapped to CBL principles, followed by an assessment of student outcomes and lessons learned by the instructors. The course has increased in popularity and feedback from students suggest the CBL format is a large reason. Graduated students also see the value of CBL in their careers, beyond traditional engineering training. The time needed by both students and instructors to execute a course is seen as a possible limitation and requires dedication to the approach. CBL is recommended for course instructors working with complex energy systems, particularly in prosumer situations, where relationships between technological, economic, and social aspects are present.

Keywords: Challenge driven education, solar energy systems, prosumers, simulation, multi-objective

1. Introduction

Interest and application of challenge based learning (CBL) in higher education has grown significantly over the past decade, and is commonly seen as an effective method for engineering students to expand their disciplinary knowledge into socio-economic spaces (Gallagher and Savage, 2020). While a commonly accepted definition is lacking, a proposal from Malmqvist et al. (2015) is oft cited:

Challenge-based learning takes places through the identification, analysis and design of a solution to a sociotechnical problem. The learning experience is typically multidisciplinary, involves different stakeholder perspectives, and aims to find a collaboratively developed solution, which is environmentally, socially and economically sustainable.

Likewise, Leijon et al. (2021) identify several keywords from the Apple computer company's definition (2008), where the term "challenge based education" was coined, which present many similar themes: multidisciplinary, teaching and learning, technology, real-world problems, collaborative, communities, ask, subject area knowledge, solve challenges, take action, and share.

The course "Solar energy systems for buildings and cities" was a graduate level course (year four of a five-year master's degree) at KTH Royal Institute of Technology designed primarily for students in the Sustainable Energy Engineering (SEE) program. It was developed in 2016 around the CBL model and given six times between 2017 and 2022. While many (if not most) courses in the program rely on project-based learning in groups, the CBL aspect of this course make it somewhat unique. Due to the restructuring of the master's program, many topic-specific courses have been absorbed into larger courses on integration, including this course. The experiences of developing and executing the course are presented here as a case study in CBL as applied to solar energy engineering and aim to act as a reference and inspiration for future course development.

2. Course Structure

The overall aim of the course is to give students a fundamental understanding of solar energy applications in the built environment and skills in designing solar energy systems. Since the students are mostly coming through the SEE program, it is expected that they have prior understanding of solar radiation, the basic function of solar thermal collectors, and the photovoltaic (PV) process, however it is not given as a strict prerequisite requirement. This course is therefore focused predominantly on systems design and the specific intended learning outcomes (ILO) are:

doi:10.18086/eurosun.2022.19.05 Available at http://proceedings.ises.org

- ILO1: Describe the principles of solar thermal and photovoltaic technologies for buildings, including; design, economics, and application
- ILO2: Analyze and communicate the techno-economic characteristics of solar energy systems for the built environment

ILO1 is examined using an individual home assignment consisting of short answer questions (100-200 words) where students demonstrate critical understanding of the material. ILO2 is examined using a group project (three students per group) with a final report (approximately 30 pages) and a final presentation (10 minutes). The course is worth 6 ECTS credits (1.5 to ILO1 and 4.5 to ILO2) and is given over nine weeks, meaning that each student is expected to spend, on average, 16 hours per week on the course. In total there are 14 hours of lecture (not including the two-hour introduction), eight hours of software demonstration, a two-hour seminar at the course midpoint and a two-hour final seminar. In this case, one “hour” consists of 45 minutes due to breaks within and between course events. There are also four occasions where the groups can register for a 30-minute consultation to get personalized assistance (analogous to office hours), and a study visit to the department’s rooftop laboratory where they can see a multitude of solar technologies related to the instructors’ research.

The course is designed around the CBL project with nearly all course activities work to support its completion. The lectures and software demos are heavily biased to the first three weeks of the course, whereas later weeks are open for project/assignment work. The first lecture (after the introduction) takes a high-level view of solar energy in buildings by introducing technical and economic key performance indicators (KPI). Since both solar thermal and PV systems will be analyzed, it is critical for students to think early on about what they hope to achieve in their design and how it relates to the goals of their client, the occupants, and society. Educational content is delivered in a 4+4 format, where a topic receives four hours of lecture and four hours of software demo in a single week. This approach helps reinforce concepts through repetition; the lectures present the theory which is then repeated and animated through the construction of a functioning model. The final four hours of lecture are dedicated to systems integration, which also has some repetition of previous concepts, and but is largely aimed at demonstrating more clearly the tradeoffs involved with various design choices.

The assignment follows a similar structure to the course content and is designed to test recall and explain core concepts. Since the assignment is given on the first day and is due (at latest) the same day as the project, the questions are also written in such a way that they can also help form critical connections for completing the project. For example, asking students to contrast and compare two relevant KPIs in the assignment can help them formulate their project analysis and avoid mistakes. Three weeks before the final seminar, there is an early deadline for the assignment that gives students the opportunity for bonus points. The points are the external motivation for students, however the educational motive for doing this is twofold; first it means students will focus on understanding concepts which will benefit their work in the project, and second it better distributes workloads, which inevitably piles up at the end the course (and all their other courses on top of it).

Due to the mixture of technical, economic, and social aspects, a single textbook could not be found to base the course on. Specific chapters from two books are instead referenced in the lectures and recommended for further reading; for solar thermal it is venerable Solar Engineering of Thermal Processes (Duffie and Beckman, 2013) and for PV it is Solar Energy Engineering (Kalogirou, 2009). These however only provide core concepts, and more nuance on market forces and policy are provided through the IEA’s annual Solar Heat Worldwide (Weiss and Spörk-Dür, 2021) and Trends in Photovoltaic Applications (IEA, 2021). Finally, a number of scientific articles and reports are referenced in the lectures and provided as additional resources for voluntary reading beyond the core concepts.

There are two computer programs to execute the analysis – Polysun (Velasolaris, 2020) for solar thermal and System Advisor Model, or SAM (National Renewable Energy Laboratory, 2020) for PV. In the first few years, Polysun was used for both technologies, however row-to-row shading of the modules was also applied to the building, causing changes to heating loads and inconsistency in the analysis. SAM also has a superior parametric analysis feature, which makes completing the project easier. As an educational tool for building heating systems, Polysun has the advantage of combining an intuitive graphical interface with a low barrier to entry. Students are able to get working models quickly and can reference one of the many templates if needed. Even though the instructors are using TRNSYS in their research, the steep learning curve, difficulty in debugging models, and greater effort needed to export and post-process results make it challenging to use in a shorter course. Even in a five-month long solar energy course, students have asked for more time to learn TRNSYS or dedicated software training (Kummert, 2016). Polysun is also more commercially oriented, meaning it is more likely to be used in a professional environment, whereas TRNSYS tends to be used more often in academia.

3. Challenge Based Learning Project

The group project is presented to students as though they are energy consultants, and their client is a real estate developer that wants a solar energy design strategy for multi-family housing units across Europe. The building is standardized (i.e. identical in all locations) and as much roof area as possible is left open for solar energy capture. The firm is technology agnostic, therefore the students must deliver the "best" system that "optimizes" the technical and economic potential of the roof space.

Placing "best" and "optimize" in quotations is a key aspect of the description, as it represents the problem formulation portion of CBL. The students are forced to think about what "optimum" means, for the client (real estate company), the building's eventual owners/tenants, and for society (i.e. climate change or other environmental factors). They are given the freedom to define "optimum" for themselves (with motivation), necessitating their own selection of technical, economic, and environmental key performance indicators (KPI) and the methods of applying them.

3.1 The Target Building

All groups work with an identical building: a four story, multi-family house with 18 apartments and an air-to-water heat pump to supply domestic hot water and space heat, with the Polysun system diagram shown in Figure 1. Students can optionally use a system with both heating and cooling if they are in a cooling dominated climate. The building demand and mechanical system are pre-defined and provided in a Polysun file, meaning students are only asked to add solar energy supply to the system. The roof is flat with an area of 16 x 28 m available for collectors or modules, and the long side of the building is facing south. There is also an option to install building-integrated PV via translucent glass in the balconies on the southern facade, which are already planned to have traditional glass.

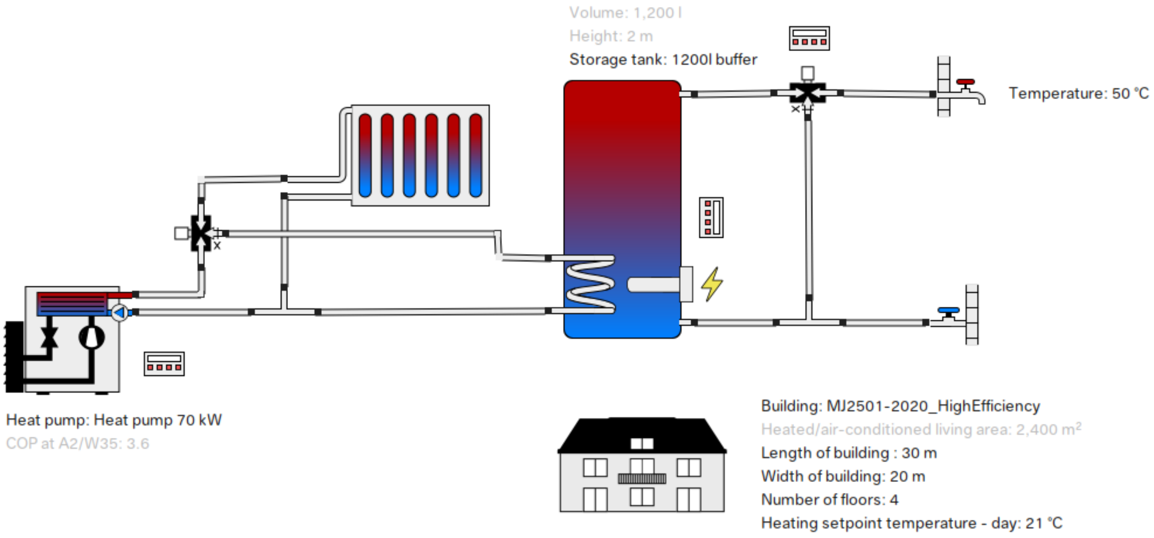

Fig. 1 - Baseline heating system provided with the target building

3.2 Locations

There are eight locations across Europe with each group assigned to one: Stockholm, Copenhagen, Paris, Munich, Milan, Barcelona, Thessaloniki, and Izmir (Turkey). The locations are specifically selected to represent a diverse range of climates and solar generation potential, as well as electricity prices and generation portfolios with varied greenhouse gas emissions, as shown in Table 1. For example, Copenhagen's greater need for heating (i.e. electricity demand) combined with high electricity prices can produce better economic outcomes than Izmir, even though Izmir has 70% more annual irradiation. Climate files using the same data but formatted for each program are provided, and aside from electricity prices, which are location specific, all other economic boundary conditions are standardized across all groups. This includes a selection of solar collectors, PV modules, and PVT collectors available in each program's library, a list of generic components (e.g. tanks, valves, inverters) with prices, and prices for installation.

Tab. 1 - Solar, electricity price, and greenhouse gas emissions of each location

Location	GHI	Avg. Temp.	Purchase	Sell	GHG
Units	*kWh/m²/yr*	*°C*	*€/kWh*	*€/kWh*	$g_{CO2\text{-}eg}$/*kWh*
Copenhagen, Denmark	982	8.3	0.241	0.046	386
Paris, France	1070	11.1	0.161	0.071	93
Munich, Germany	1124	8.0	0.259	0.072	574
Thessaloniki, Greece	1566	15.4	0.143	0.070	757
Milan, Italy	1292	11.8	0.189	0.073	448
Barcelona, Spain	1460	15.7	0.190	0.067	312
Stockholm, Sweden	923	6.5	0.155	0.054	25
Izmir, Turkey	1690	16.7	0.085	0.066	750

3.3 Analysis Approach

As mentioned above, the students are given the freedom to choose their own design goals and KPIs with which to measure those goals, and their analysis must motivate their "optimal" recommendation to the client. This is achieved through several rounds of semi-structured parametric analysis. Given the large number of variables, particularly within solar thermal systems, it is impractical to test every possible configuration parametrically in a single course. The analysis structure, shown in Table 2, gives students a process to follow and is also used in examination. For example, if a group is only interested in achieving an E-grade for the project, they only need to successfully complete the basic level analysis. Generic settings are provided at lower levels to make the analysis possible, which are then tested/replaced later on. For example, it is suggested to use a single inverter for each row of the PV system to make it easy to test all possible capacities and tilts in a single parametric analysis, however an inverter selected specifically for the final design must be made at the end of the analysis to receive the highest grade. The students are advised to study each technology independently using comparable KPIs. Once completed, they can decide if they wish to take one technology, mix the two, or use a PVT hybrid. Again, this decision should be made using their selected KPIs to demonstrate that their design is brings the solution closer to their stated goal(s).

Tab. 2 - Parameters tested at the three levels of analysis

Level	Thermal	Photovoltaic
Basic	Collector area Tilt angle Tank size	Capacity Tilt angle Azimuth
Intermediate	Tank connections Temp. sensor	Module type Building load
Advanced	Tank splitting Controller settings	Inverter selection Battery / BIPV

There is a small difference in the approach for thermal and photovoltaic systems. With solar thermal, the design specifications chosen at one level can be locked in when moving up to the next level. For example, once the collector area is chosen, it can remain at that size when altering control parameters. For PV, it is expected to repeat the full parametric analysis for capacity and tilt angle at the intermediate level. This is done for two reasons; first, the results can vary significantly, particularly with testing the different building load profiles for heating/cooling only or the full site load with apartments included. And second, SAM makes it relatively easy to accomplish this once the parametric study is established so the workload is not an excessive burden. A common challenge through the project is the balance of tasks and time, which is discussed further throughout the paper.

4. Student Outcomes

In the early years of the course, the delivered projects often lacked technically successful systems. Students were given free reign and encouraged to try nearly any design or technology they liked so long as it could be qualitatively motivated with thermodynamic theory. This limited their ability to complete a parametric analysis, or in the worst cases, get a successfully running simulation. Many were enticed by advanced concepts like borehole thermal storge, which is tantamount to attempt running before being able to crawl. This led to a standardized mechanical system being provided (Figure 1) and adding more analysis structure (Table 2), providing the students with a clear(er) pathway through the design process. This was particularly helpful to students experiencing a CBL project without clearly pre-defined goals for the first time in their engineering education.

Most students tended to prioritize the needs of their client, the real estate developer, and make their aim economic maximization. The KPI of choice does vary between internal rate of return (IRR) and net present value (NPV), with most using NPV. This is likely due to one of the lectures demonstrating how optimizing NPV can lead to larger system designs, so it is seen as a middle way as compared to optimizing for IRR or maximizing solar fraction. In practice, students find multi-criteria optimization challenging and resort to an interactive approach of reevaluating their priorities once they've generated results. This often leads to somewhat subjective system designs that aim to balance solar fraction with economic benefits. The other most common design goal is to maximize solar productivity so long as NPV remains positive, however this is usually only used by one or two groups per year.

From a design standpoint, the analysis structure somewhat limited the types of solar thermal systems explored. Only once since the introduction of the standardized mechanical system did a group present a combi-system – the rest are all domestic hot water only. At no point are students told they cannot study combi-systems, some are even encouraged when their location and goals make it more suitable, but the short course period, a desire to complete all level of the analysis, and no higher grade for the extra work makes it easy to simply add solar thermal to the hot water tank and avoid the extra headaches of replumbing the heating circuit.

Conversely, the open nature of the CBL project leaves room for motivated and interested students to explore novel ideas and go beyond the standard analysis structure. One example, shown in Figure 2, is a case where students used the concept of a Pareto frontier, which was pulled in from a different course given in parallel, to display results and select a system balancing technical and economic factors. There have also been several groups who created their own multi-criteria index based on technical, economic, and environmental KPIs to remove seemingly arbitrary decisions when balancing non-comparable benefits. An important learning point with this approach is that the weighting of each KPI is also subjective, meaning the index does not escape the subjectivity of the decision, only hides it. In another case where the economic outcomes were not as positive, the students made a carbon pricing sensitivity analysis as part of a policy recommendation to encourage solar development in their region. The CBL structure helps to drive their own curiosity to do the extra work, even if it doesn't necessarily lead to additional grading points.

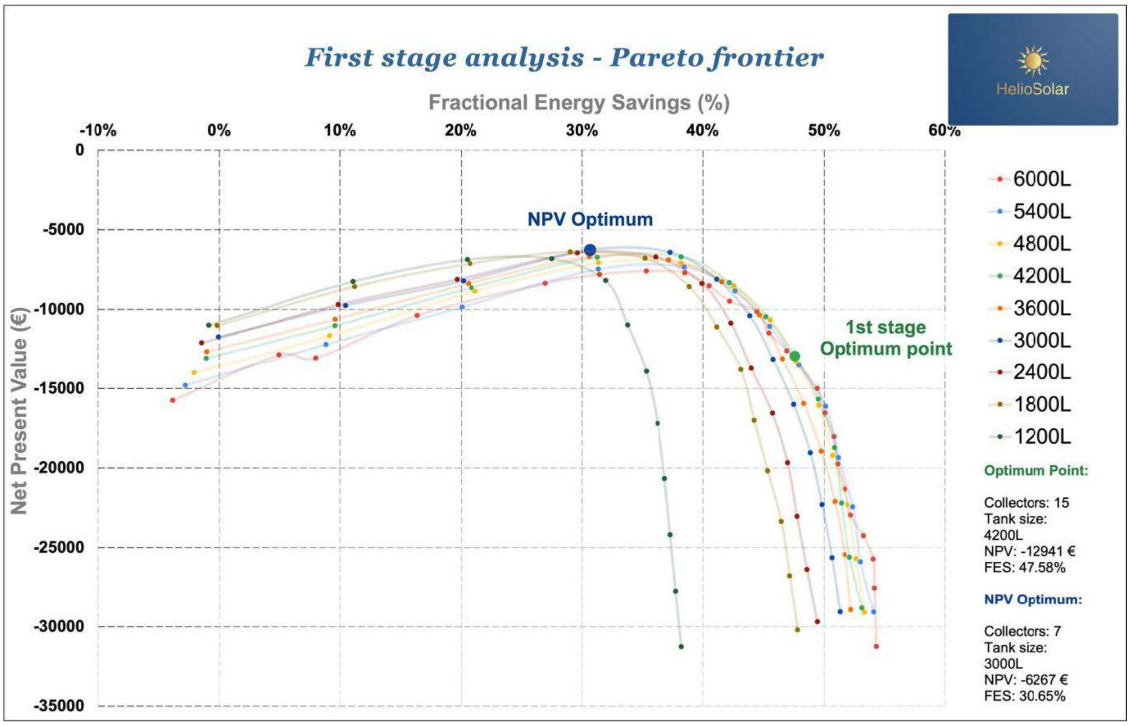

Fig. 2 - Example of a Pareto frontier used in the solar thermal analysis

A limitation of the CBL format as it is applied here is that comparison between projects is often difficult or impossible due to the differences in design objectives, KPIs, and quality of analysis. One aim of the project structure is that students should see how design outcomes vary with the influence of climate and energy prices, expanding the scope of the project to all of Europe. This does happen to a degree, however if a group uses their own novel KPI or makes a mistake in its application, then direct comparisons are not possible. At one point it was considered to require a certain set of KPIs to be used and reported ahead of the final seminar, which would make it possible to present all the results together and strengthen this part of the learning. However, mistakes would still be present, limiting the effectiveness, and it would take away from the problem formulation. The need to define the problem/goal for themselves is what distinguishes the course from being challenge based versus project based, which was considered more valuable than a quantitative comparison of each location. A qualitative comparison is still made as part of the closing comments of the final seminar and is sufficient given the wide range of uncertainty present in the results.

5. Student Feedback and Lessons Learned

In all KTH courses, student feedback is primarily collected using standard surveys sent out once final grades have been delivered. There are several versions of the survey with different lengths, and for this course the full 22 question survey has always been used. Students respond anonymously and are asked to score their agreement with a given statement from on a seven-point Likert scale ranging from “Strongly Agree” to “Strongly Disagree.” The wording is such that stronger agreement (i.e. higher scores) are considered positive, and the results are converted from a -3 to +3 rating in the survey to a 0 to 7 scale when reported to instructors. Students are also able to leave a general comment and specific comments for each question. In its six years, the course has garnered a strongly positive response with an overall score of 6.2. This is in part due to it being an elective (note the high score for Question 1 in Table 3), mandatory courses often get more criticism from those unhappy to be forced into it, but there are some common themes in the feedback related to CBL that support the high score.

Table 3 lists the most relevant questions to CBL and the general structure of the project. Question 3 on being able to learn by trying their own ideas, is one of the core principles of the project and has received a high score of 6.4. Many students stated that they had never had a project or course designed in this way and that they found it very interesting and valuable. There are however a small number of students who found the whole concept very confusing and lost a lot of time just trying to understand how to approach the project. This is reflected in Question 13 on expectations, which still had a high average of 6.1, but also has a high variance. Students also found the course challenging in a stimulating way (Question 4) which ties back to the extra work they are willing to do to explore their designs.

Tab. 3 - Sample of student survey questions with results from all six years (74 respondents out of 216 total)

Question	Minimum	Weighted Average	Maximum
1. I worked with interesting issues	6.3	6.7	6.9
3. I was able to learn by trying out my own ideas	5.8	6.4	6.8
4. The course was challenging in a stimulating way	5.8	6.2	6.6
5. I felt togetherness with others in the course	5.0	5.8	6.2
13. I understood what I was expected to learn to obtain a certain grade	5.0	6.1	6.9
21. I was able to learn by collaborating and discussing with others	5.8	6.2	6.7
22. I was able to get support if I needed it	6.4	6.6	6.8

A somewhat surprising result is the poor score on Questions 5 regarding interactions with fellow students. This is likely due to conflicts within project groups, which varies a lot year to year, and is a common limitation with group projects not unique to this course. It is also an issue of gender given that women have often (but not always) given a worse score for Question 5, in some years much worse. Question 21 has a much higher score and is likely based on the inter-group discussions that occur in the computer lab and in seminars. Comments on the mid-term seminar reveal that in the week leading up it is felt as a source of unnecessary stress given that the seminar is ungraded and comes relatively early in the design process. Students find it unusual to make a presentation where you might not even have results, just an assessment of the problem and their plan of attack to solve it. Afterwards, it is viewed as one of the most useful points in the project because they can see how others in the course are thinking about the problem and it can help them correct course or spark new ideas. Moving forward it is wise to take this positive collaboration found between groups and ensure that the same positivity is experienced within them.

What is abundantly clear from both the survey score of Question 22 and the student comments is that instructor support is critical in a CBL project like this. The relative openness of the task means students can get lost quickly, and if a mistake is found late in the course it can mean many hours of last-minute re-simulation. This makes frequent and useful feedback is critical. The mid-term seminar is already mentioned, where the instructor makes the majority of questions/comments during discussion, but students are also able to submit a mid-term report for more detailed feedback. Then there are the weekly consultations, which over the years have been found to be best when 30 minutes long. Too short and the students run out of time and/or the sessions run behind, too long and a lot of the instructors' time is taken up.

The CBL approach means each student group is on their own journey, which does require more time and mental effort of the instructors. When course numbers are relatively low (20-30 students) it is manageable, however there have been years with 50 students (16 groups) where it becomes challenging, and a teaching assistant is necessary. The same issue extends to examination, which is done via a 30-to-40-page report and 10-minute presentation that involves careful reading to extract methods and meaning such that fair examination on disparate learning aspects can be made.

The overwhelming sentiment from students is that they wished they had more time. Not that the workload was too much, many state they spend the same or less amount of expected time on the course, but that they want more time to explore and contemplate. The short nine-week period means that they need to rush the analysis and make decisions sooner than they would like. The rushed schedule also leads to specialists forming within the group, where one or two take on solar thermal and the other(s) take PV, to make the project more efficient. With more time the students would have the ability to be more hands on with each technology if they wished.

In addition to formal course surveys, informal interviews are made with one or two students each year and has also extended to students who have graduated and working in solar developers or engineering consultancies in Europe and North America. The interviews with students directly following the course largely reinforces the insights gained during the survey, with a bit more detail and nuance that can be used to adjust the course. The feedback from those working with solar in the field is that the techno-economic analysis needed is surprisingly easy thanks to their education and that it is the non-energy related factors that provide the greatest challenges in their jobs. They say that the experience of working a CBL project (referring to the course, not CBL by name) helps them assess and solve challenges tangential to their core discipline.

6. Conclusions

This paper presents a case study of challenge based learning as applied in a graduate level solar energy engineering course. Over its six-year lifetime, the course grew to become one of the most popular electives in the department with one of the highest student evaluation scores. Many students specifically mention the project format, with its real-world framing and flexible approach, as a particularly positive experience. Graduates have stated that critical thinking induced by the CBL format is particularly valuable in their careers, where the hard problems are often unstructured. The relatively individualized experiences of each student (or student group) mean that executing the course requires dedication from the instructor(s) to give timely and useful feedback, as well as be available for individual consultations.

Actionable points of improvement from this case study are two-fold – to provide the maximum amount of time available for the course (i.e. a full semester) and to minimize the potential conflict within groups. The former is straight forward, the latter is more challenging. There will always be a distribution of priorities and motivation within students, so grouping them together, especially if they are unknown to each other prior to the course will always have the potential for conflict. There are potential solutions, such as shuffling groups during the course, but any solution needs to be considered withing the context of CBL such that the most valuable benefits are not lost.

The death of the course is a product of solar energy's success as a technology. Solar energy systems are now expected or even regulated on many new building developments around the world. Even prior to the 2022 energy crisis in Europe, the retrofit market was returning to prominence after a 10-year lull. Solar is now an integral part of building and urban energy systems and higher education programs/courses need to adapt (Witzig et al., 2016). The CBL format provides an excellent platform for students to learn about complex energy systems and their technical, economic, environmental, and social characteristics. CBL is recommended for course leaders hosting and developing sustainable energy courses/programs, particularly for prosumer energy systems.

7. Acknowledgements

I would like to thank the course examiner and my partner in building this course, Hatef Madani. Thank you also to Chris Bales and Bengt Perers, for providing excellent lectures on solar thermal systems during our early years, and to Viktoria Martin for providing lectures on solar energy storage.

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