Using TRNSYS in a graduate course on solar energy engineering

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Abstract

This paper presents a graduate solar energy engineering course which relies on the TRNSYS simulation tool to engage students in the learning process through design and analysis activities. The course learning objectives are discussed in relation to Bloom's revised taxonomy. The paper then presents an overview of the course contents, as well as teaching and assessment methods. Student feedback has been overwhelmingly positive on the use of TRNSYS, and on the combination of theoretical notions and practical, simulation-based design exercises. The students also pointed out the lack of software training material specific to the subject, which leads to difficulties in selecting and configuring the appropriate components.

Keywords: education; teaching; solar energy; simulation; modeling; TRNSYS

1. Introduction

Most university-level courses on renewable energy are taught at the graduate[1] level, either as part of a program focusing on that topic, or as elective courses in more general programs (Kandpal and Broman, 2014). Renewable energy education at Polytechnique Montréal followed the general trend in North America, where renewable energy education in universities took off in the late 20th century, in the wake of the oil crises. Solar energy was often among the first graduate courses created, with many instructors adopting the seminal "Solar Engineering of Thermal Processes" textbook currently available in its 4th edition (Duffie and Beckman, 2013). At the beginning of the 21st century, dwindling research and education funding had resulted in only about 10 US universities offering regular solar energy courses, down from around 150 in the early 1980s (Goswami, 2001). The solar energy course at Polytechnique again followed that trend; it was not taught for about 10 years before being reinstated in 2011.

The course described in this paper is known as MEC 6214 – "Énergie Solaire et Applications" (Solar energy and applications). It is taught once a year, during the winter term (January to May). The current course contents and teaching methods are the results of 6 years of trial and error by the author, although the basic structure and the learning objectives remained the same. As pointed out by Kandpal and Broman (2014), "*the scope and contents of a course essentially depend upon the expertise, interest(s) and biases of the course teacher*". The course described in this paper is no exception: both the theoretical aspects addressed in the first part of the course and the practical, simulation-based approach are a result of the author's experience and level of comfort with the selected topics and tools. As a consequence, this paper does not pretend to represent the best practice in teaching solar energy engineering. It represents the author's contribution to the sharing of teaching methods and materials, and an example of how a detailed simulation program as TRNSYS can enrich a solar energy course and help engage students in the learning process.

> Note: The author has made some teaching material available on an open website accompanying this paper:
> https://moodle.polymtl.ca/course/view.php?name=mec6214p (most material is in French at this time)

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[1] "graduate" in the paper title and in the text refers to the level of a student who has graduated from a university-level "undergraduate" program, often a Bachelor's degree (~4 years). The term is frequently used in the USA and in Canada, while "postgraduate" is often used with the same meaning in Europe and some other countries.

2. Prerequisites

The general policy at Polytechnique Montréal is to have no prerequisites for graduate courses. While most students taking the course have completed or are about to complete a Bachelor's degree in mechanical engineering, students from other engineering branches and sometimes other backgrounds (architecture, economics, physics) have also taken the course. The required prior knowledge is limited to basic thermodynamics and heat transfer: energy balance of closed and open systems, conduction, convection and radiation heat transfer, heat exchangers. Reading material is provided to cover these topics, e.g. Chapter 3 in (Duffie and Beckman, 2013) or thermodynamics and heat transfer textbooks, but no special tutorial sessions are organized. No prior knowledge of the software tools (especially TRNSYS) is expected, but a small number of students have typically been exposed to them in other undergraduate or graduate courses. In particular, TRNSYS is used to some extent in many of the core courses given at the school on building physics, HVAC systems, building energy modeling, and other renewable energy systems (i.e. geothermal).

3. Learning objectives

After taking the course, the students should be able to:

- Describe the environmental and economic context relevant to solar energy engineering
- Assess the solar energy resource of a site
- Calculate the solar radiation incident on a surface (beam, diffuse and ground-reflected components)
- Explain the principles of solar collectors and solar energy systems
- Calculate the performance of solar collectors
- Analyze the economic and energy performance of solar energy systems[*]
- Design and simulate the performance of solar energy systems
- Justify the use of given renewable energy technologies (wind, solar thermal, solar photovoltaic) in particular applications

[*]It should be noted that, adopting the approach of Duffie and Beckman (2013), the course focuses on solar thermal systems but also covers more briefly solar photovoltaic (PV) systems and wind energy systems.

Using Bloom's revised taxonomy (Anderson and Krathwohl, 2001), some learning objectives listed above fall in the lowest 3 categories of educational objectives in Figure 1: remember, understand, and apply (where the "remember" objective is not mentioned explicitly but implied). These categories are more present in the first part of the course ("fundamentals" part, see below).

Create
Produce new or original work
Design, assemble, construct, conjecture, develop, formulate, author, investigate

Evaluate
Justify a stand or decision
Appraise, argue, defend, judge, select, support, value, critique, weigh

Analyze
Draw connections among ideas
Differentiate, organize, relate, compare, contrast, distinguish, examine, experiment, question, test

Apply
Use information in new situations
Execute, implement, solve, use, demonstrate, interpret, operate, schedule, sketch

Understand
Explain ideas or concepts
Classify, describe, discuss, explain, identify, locate, recognize, report, select, translate

Remember
Recall facts and basic concepts
Define, duplicate, list, memorize, repeat, state

Figure 1: Bloom's revised taxonomy, adapted from (Armstrong, 2016)

The upper categories (Analyze, Evaluate and Create) rely on performance simulation with TRNSYS: students learn how to design solar energy systems first by analyzing the performance of pre-defined systems, by assessing the impact of design changes, and then by proposing and comparing different designs. In theory, it would be possible to perform these activities without relying on software tools, e.g. by using monthly

design methods such as F-Chart (Klein, Beckman and Duffie, 1976). However, using simulation programs such as TRNSYS allows to consider a much larger variety of systems combining different technologies (e.g. solar thermal, solar PV, and wind); it also allows investigating the dynamic behavior of complex systems and control strategies.

4. Teaching and assessment methods

The course follows the typical pattern for graduate courses at Polytechnique Montréal, which consists of a weekly 3-hour lecture (there are normally 13 lectures per term). There are no formal labs or tutorials, but the students are expected to dedicate time to the course at home for personal study, homework assignments and exam preparation, for a total of 96 hours. The total theoretical workload for students is 135 h over the teaching term, which corresponds to 3 credits at Polytechnique Montréal. It can be loosely translated to 5 or 6 ECTS (European Credit Transfer and Accumulation System).

The course is based on "Solar Engineering of Thermal Processes" (Duffie and Beckman, 2013), which has been one of the most popular textbooks to teach solar energy engineering since the 1970's, in North America and throughout the world. The course mainly relies on the first 6 chapters for the "fundamentals" part (see below), which is taught in conventional lectures with homework assignments.

Engaging students

There is increased evidence that traditional lectures are not the most efficient at maximizing learning and course performance in Science, Technology, Engineering and Mathematics (Freeman *et al.*, 2014). Students benefit from active learning, which is defined by the adoption of instructional practices that engage students in the learning process, such as collaborative, cooperative, and problem-based learning (Prince, 2004). While promoting student engagement is an unquestionable objective, it can be challenging to realize in a course with 39 hours of faculty-students contact and a relatively large number of students (the average course enrollment is above 30 students per term, with an upward trend).

The first approach taken to engage students in this course is to try and bring some collaborating learning in the biweekly homework assignments. Students solve the assignments and submit their results individually, but a significant part of the next lecture (roughly one hour) is taken to discuss the problem and the results. The students and instructor diagnose the errors in submitted results. In many cases, students work on different datasets, which was originally intended to prevent plagiarism, but has proven useful in transforming individual efforts into a form of teamwork, where all students contribute one part of a larger parametric analysis.

The second approach to engage students relies on simulation-based problems (assignments or intermediate steps of the final project). During the second half of the term, the time spent giving conventional lectures is considerably reduced, to approximately 1 teaching period (50 min). This leaves two periods for participative activities. Instead of the conventional classroom used for the first part of the term, the course takes place in a computer lab, which allows students to perform simulations during the class. They can analyze their results and diagnose their problems with the help of the instructor, within the constraints imposed by the number of students (i.e. each student gets relatively little time for individual assistance).

Assessment methods

The assessment relies on individual homework assignments (biweekly individual assignments, worth 1/3 of the final mark together), on a written exam (individual, 1/3 of the final mark), and the final project (groups of 2 or 3 students, 1/3 of the final mark). The weight of these different assessments have evolved over time, in response to student feedback that the initial weight for the exam (40 %) did not give a fair share to the other activities. The exam is organized as a mid-term assessment, which comes after the lecture-based "fundamentals" part of the course. It is a conventional written exam, during which students only have access to a 2-page document that they have created themselves and to a non-programmable calculator. In terms of Bloom's taxonomy, the learning objectives assessed in the exam mostly fall in the lower 3 categories (remember, understand, apply), with some attempts to reach levels 4 and 5 (analyze and justify), e.g. with questions asking to define a solar fraction that would apply to a particular system. The homework

assignments ask for numerical answers but also in many cases for a report with some analysis and critique of the results and assumptions, which can be seen as pertaining to categories 4 and 5: analyze, and evaluate. This is especially true for the assignments that use TRNSYS simulations. But to really attain the highest category of educational goals ("create", i.e. design, formulate and investigate), the course relies on simulation-based exercises, and this level is probably only reached during one or two assignments, and the final project, which is a group activity (2 or 3 students).

A practical exam using TRNSYS was introduced in 2012 and 2013. This 2-hour exam was taking place right after the conventional written exam, and was originally intended to test whether students had gained a sufficient understanding of how the program can be used to analyse solar systems, but it proved difficult to test more than basic TRNSYS skills, which was not in line with the learning objectives, so that exam was withdrawn in 2014 and for following years.

5. Use of TRNSYS and other software tools

Literature review: courses using TRNSYS

The literature on teaching solar energy with TRNSYS (or with other simulation tools) is scarce. A few papers report on successful attempts in universities across the world to use TRNSYS in teaching various subjects, from building energy systems to solar energy engineering.

TRNSYS is used in several courses at Polytechnique Montréal, from 4th year (BEng) courses in building heating and cooling mechanical systems to graduate courses on geothermal systems and solar energy (the course described in this paper). It is also used in a graduate course on building energy modeling (Bernier *et al.*, 2016). Students in graduate programs such as the recently created course-based Master in energy engineering are likely to take several of these courses (if not all), which offers synergies and reduces the student effort to learn the software.

Megri (2014) discusses the use of TRNSYS in the department of Architectural Engineering at North Carolina A&T State University. The paper presents a methodology for students to build their own model, perform numerical experiments, and analyze the results. The selected case study is a solar-assisted ground-source heat pump system coupled to a multizone building. According to the author, students prefer easier-to-use programs such as EQuest, but TRNSYS has the benefit of not restricting the type of systems which are analyzed. The instructor needs to master the TRNSYS program and the subject areas.

Charles and Thomas (2009) use TRNSYS in undergraduate courses for engineering and architecture students. The program is coupled with CONTAM for bulk airflow analysis, and other tools are used for climate analysis and Computational fluid Dynamics (CFD). The focus is on encouraging teamwork and benefitting from complementary experience, and simulation is not performed by all class students but rather by an external expert, the instructor, or a few volunteer students. The authors report that students find TRNSYS difficult and are more attracted towards the CFD software. The latter can produce visually attractive results and the authors express that using a little bit of "colorful fluid dynamics" is a necessary evil to generate interest. In spite of the difficulties, the authors conclude that simulation helps students understand the iterative nature of the design process and makes them aware of various physical phenomena. It is also a common platform to support collaboration.

Gómez-Moreno (2015) describes how TRNSYS is used in an undergraduate course on HVAC systems in Industrial Engineering at Universidad de Jaén. Transient simulations are used to help students understand the dynamic behavior of HVAC systems, enhancing the knowledge of steady-state performance that they have gained through more conventional teaching methods. The program is also used to introduce renewable energy in a course that otherwise focuses on air-conditioning systems. The authors state that a software program like TRNSYS is the ideal tool for the students to acquire new competencies and to understand the dynamic behavior of complex systems. It also has the benefits to promote student engagement and increase the motivation. They present the results of a student survey showing that 80 % or more of the students have found that the simulation tool is useful to complement the lectures, help understand the operation of HVAC and solar systems, increase their interest in the course, and improve the quality of teaching.

Gravagne *et al.* (2008) report on the use of TRNSYS in a graduate elective course on solar energy in the department of mechanical engineering at Baylor University. The authors mention the use of TRNSYS for LEED certifications of buildings and for SRCC certifications of solar thermal systems as key aspects in support of selecting the program, as well as a series of features introduced in version 16 that made the software more relevant to classroom use. TRNSYS was only used midway through the class, and it was used to revisit problems that had been solved by hand or with generic software such as Excel or Matlab. One benefit of this approach is that students had a deeper understanding of the software assumptions and results. They could identify spurious results more easily after developing intuition by obtaining results the "hard way". TRNSYS was then used as a design tool in the final project. This allowed students to perform activities (design) for complex systems that they would not have been capable of analyzing without the program. The "mixed quality" of the documentation required a careful preparation by the instructor, so that students are not frustrated by hard-to-find information. Cryptic error messages, and non-standard units, such as the use of kJ/h for energy rates, are also pointed out as weaknesses. But overall, TRNSYS improved the learning experience and most students expressed their wish to start using TRNSYS earlier in the course.

These examples show that TRNSYS can be used successfully for teaching solar energy engineering and other topics. But there is a need for a larger body of shared knowledge about how the tool can be used efficiently for teaching and learning, and there is also a need for publicly available material to support that objective. This paper and the accompanying website is the author's attempt to contribute to that material.

Why was TRNSYS selected?

Ideally, an engineering course should be tool-independent. However, the pursuit of this noble objective quickly faces practical problems: can the instructor master all the tools involved? is the time invested in software installation and basic learning justified? can all the licenses be obtained without investing too much time and money? As discussed below, the students taking this course sometimes felt that using different programs would have been beneficial, while attempts to be tool-independent (and therefore using several different tools) can lead to students being frustrated at the time and energy involved to install and master these software tools (Beausoleil-Morrison and Hopfe, 2016). In many cases – as well as in this course – students also express the need for more software training material adapted to the course (Gravagne and Van Treuren, 2008; Beausoleil-Morrison and Hopfe, 2016). Over the years, a course instructor can reasonably build specific training material adapted to a particular course for a software program, but creating and maintaining that material for several different tools seems impractical.

As indicated in the introduction, the choice of TRNSYS came naturally to the course instructor, as he was very familiar with the program and confident that he could not only use the program to obtain simulation results but also investigate its assumptions and algorithms. When teaching an engineering discipline, being able to examine the actual source code of the software is a great advantage that few commercial programs offer, and open-source alternatives are not always available. Numerous validation studies including TRNSYS have been published, such as the BESTEST inter-model comparison (ASHRAE, 2014). TRNSYS is also used as a reference tool in international standards (ISO, 2013) and certification programs (Burch *et al.*, 2012; SRCC, 2015), which is a testimony to the software relevance for solar energy systems.

TRNSYS' main advantage is probably its flexibility, which comes from its modular structure and from the well-developed libraries of component models. Components can be connected together to form a system, and then configured by modifying the relevant parameters. Assessing different system configurations only requires to add/remove components from the libraries and modify the connections, without modifying the equations and algorithms used in the model. The program flexibility is also expressed by the fact that many different *domains* (Clarke, 2001) can be analyzed together: thermal processes and electrical flows within buildings, HVAC systems and renewable energy systems can form one coupled system. This is a great advantage over some easier-to-use tools which are generally restricted to a single domain or technology (e.g. solar thermal systems for hot water production, or solar photovoltaic systems).

Flexibility has a cost: students can be overwhelmed by the numerous components and libraries, and they can define wrong connections that will result in meaningless results without being flagged as errors. If students do not know how a system operates, i.e. if they do not understand the physical processes involved and its

control strategies, they will not be able to create a TRNSYS model of that system. In that respect, it is the author's point of view that TRNSYS is fully aligned with the learning objectives of a graduate course on solar energy systems engineering.

How TRNSYS and other tools are used

During the first part of the course, students are encouraged to use generic software tools such as spreadsheets and EES (Klein, 2014) to solve sun-earth geometry and solar radiation calculation problems (e.g. anisotropic tilted radiation calculation) and radiative heat transfer problems (e.g. spectral transmittance and absorptance).

TRNSYS (Klein *et al.*, 2014) is used from the beginning for homework assignments, in parallel with hand calculations or generic tools. This is intended to familiarize students with the program and to provide practical examples of the notions defined during the lectures. Examples of assignments include assessing the incident radiation incident for different slope and azimuth angles in TRNSYS using different tilted radiation models (isotropic vs. Perez), comparing the sun position, extraterrestrial, terrestrial and tilted radiation values calculated by TRNSYS to hand-calculated values. Other authors use this two-step approach to help the students develop an understanding of underlying assumptions and algorithms, and intuition (or skepticism) when analyzing simulation results (Gravagne and Van Treuren, 2008; Bernier *et al.*, 2016). Simple solar thermal systems are also introduced (without requiring students to actually build them in TRNSYS) so that students can study the "instantaneous" (i.e. time-step) efficiency of solar collectors, and compare these values to the efficiency curve provided by manufacturers or certified performance tests. Later homework assignments include simple design exercises, mostly involving changing component sizes and control parameters. During the final project, the design exercise can be related to the "create" level in Bloom's taxonomy, as the students start with a clean sheet and a realistic set of constraints and objectives (e.g. reach a given solar fraction, attain the net-zero objective, or design a stand-alone system). In most cases the load (thermal and/or electrical) that the system must meet is provided to the students in data files or calculated using simple methods, so that the students can focus on the solar system itself.

Over the years, specific assignments were introduced which relied on other tools dedicated to PV systems and solar thermal systems, but this led to mixed feedback by students (it is good to experience different tools, but students need more time to learn how to use each of them), and to some uncomfortable situations for the instructors involving crippling software bugs and licensing problems. These problems can happen with any program, including TRNSYS, but it is obviously less demanding to deal with the peculiarities and limitations of one program than to do it for several tools, especially when the instructor and his/her team are using that one program for research on a regular basis.

Teaching how to use a program vs. using a program to teach

As shown in section 3, the course learning objectives are related to understanding and applying solar engineering principles, as well as simulating, analyzing and designing solar systems. "Mastering TRNSYS" (or any other tool) is not one of the learning objectives. Other university-level courses using simulation generally share that approach (Gravagne and Van Treuren, 2008; Megri, 2014; Beausoleil-Morrison and Hopfe, 2016; Bernier *et al.*, 2016). The emphasis should be on underlying assumptions and algorithms, and results analysis, rather than expertise with a particular tool. The key to applying simulation effectively for design and analysis is to develop confidence in the simulation while keeping a critical mind.

One approach to avoid the difficulties of using the software is to employ "simulation specialists" who do the modelling work while students focus on proposing design alternatives. Successful applications of this approach for teaching to engineering and architecture undergraduate students have been reported by Charles and Thomas (2009), who compare cases where the simulation specialist is an external expert, the instructor, or a subset of volunteer students. Reinhart *et al.* (2012) also relied on a pool of "simulation experts" to perform the simulation in a design exercise that they transformed into a game where students compete to obtain the lowest energy use intensity within predefined cost limits. The game was useful in teaching how to interpret simulation results and use them in an iterative design process, and also served as a teaser.

In a later paper, Reinhart *et al*. (2015) describe how the same "learning by playing" approach was applied to a group of 18 undergraduate and graduate students who performed the simulations themselves. The course

included a series of simulation exercises culminating in a game where the students competed to design the building with the lowest greenhouse gas emissions. The authors report overwhelmingly positive student feedback, but insist on the need to keep the complexity of input files provided to the students at a reasonable level. They insist that instructors must be intimately familiar with the strengths and weaknesses of the programs used, so that they can detect and explain wrong results caused by user errors or software limitations. They mention that for larger classes, the teaching staff (one instructor and a teaching assistant) will need to increase and the use of online tutorials may be required to complement lectures and lab sessions.

The approach taken by the author in the course described in this paper is to have students use TRNSYS themselves, individually (for homework assignments) and in groups of 2 or 3 (for the final project). The software is introduced right from the first assignment, and the emphasis is placed on obtaining and analysing results during the first weeks. Later assignments and the final project are actual design exercises of increasing complexity.

6. Course structure

An example of course schedule is provided on the accompanying website (see first page).

Part 1: fundamentals

After the introduction lecture, the first part of the teaching term (approximately six 3-hour lectures over 6 weeks) follows the topics presented in (Duffie and Beckman, 2013). Table 1 shows the topics and examples of assignments.

Table 1: Topics covered in lectures and examples of assignments for course part 1 (Fundamentals)

Topics covered in lectures	Examples of homework assignments
Course objectives, context, introduction to TRNSYS Examples of successful solar energy systems Worldwide context : energy and environment, solar (thermal and photovoltaic) resource and markets **Extraterrestrial solar radiation** Solar geometry, sun position angles, equation of time	**First contact with TRNSYS** Run existing solar thermal project Configure an output component (printer) Examine the impact of collector slope and azimuth Obtain and analyze results
Available solar radiation Measurement of solar radiation, clear sky radiation, beam and diffuse radiation, isotropic and anisotropic models for incident radiation on tilted surfaces	**Tilted radiation, SDHW system balance** Calculate incident radiation on a tilted surface Compare results with TRNSYS for different anisotropic models Perform an energy balance of a Solar Domestic Hot Water (SDHW) system using TRNSYS
Radiation characteristics of opaque materials Kirchfoff's law, spectral distribution of solar and long-wave radiation, absorptance, reflectance and emittance	**Collector absorptance and emittance, collector shading** Calculate α and ε from spectral properties and solar spectrum In TRNSYS, optimize collector rows (azimuth, slope, spacing).
Radiation transmission through transparent surfaces Reflection, absorption, and transmission, spectral and angular dependence of properties, transmittance-absorptance product $(\tau\alpha)$ **Flat-plate solar collectors** Collector energy balance, overall heat loss coefficient, collector heat removal factor and flow factor, Hottel-Willier equation, collector testing and performance data.	**Collector stagnation temperature and efficiency** Calculate (by hand) the stagnation temperature of a collector In TRNSYS, examine the dynamic collector efficiency and compare to the performance curve. Students must use certified performance (ISO or SRCC) to configure the TRNSYS components.

Example of collaborative learning through individual assignments

In some of the assignments, students are given different conditions, which are then combined by the instructor during the feedback session to provide a complete picture. One simple example is the slope and azimuth of solar thermal collectors in an SDHW system. Students are provided the TRNSYS project shown in Figure 2 and are asked to assess its performance for a given slope and azimuth angle. All student answers are then combined and used to draw plots of the collector useful energy (Figure 2, top right) and collector efficiency (Figure 2, bottom right) for all slopes and azimuth angles. This is used to discuss the fact that the collector output is not necessarily maximum at the maximum of incident radiation (not shown in the figure) and that the collector efficiency does not really show where the system output will be maximum.
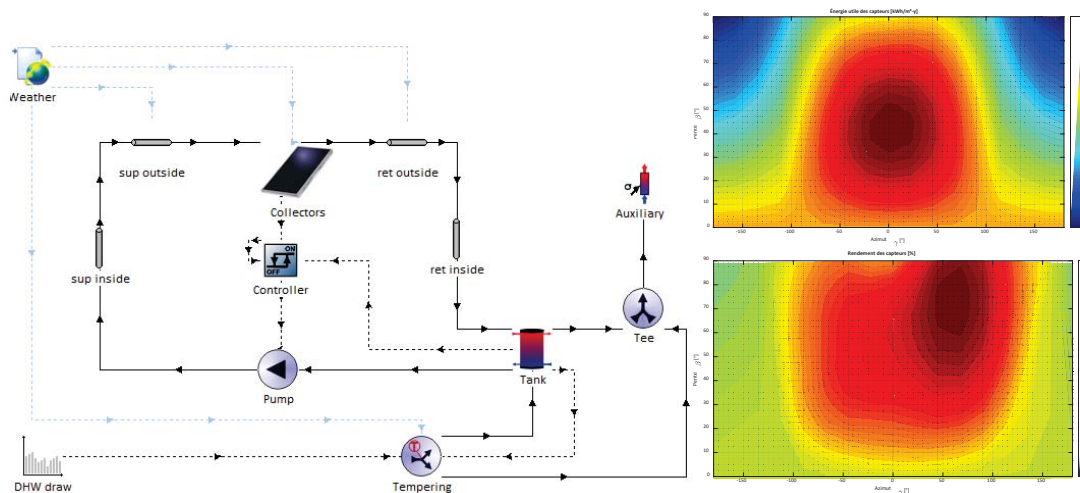

Figure 2: TRNSYS model of an SDHW system and example of results for different orientations and slopes

Part 2: applications

The second part of the teaching term (approximatively six 3-hour sessions) combines short lectures with practical design exercises. The course focuses on solar thermal applications for domestic hot water and space heating, but concentrating solar power generation and solar cooling are also covered. Photovoltaic systems are considered from a design perspective in combination with solar thermal systems, e.g. to design net-zero buildings. Occasionally wind energy is also introduced in the design of stand-alone systems. The subjects covered are sometimes adapted to make room for a graduate student who presents his/her work. Past examples include solar thermal/photovoltaic collectors, and control / fault detection of solar thermal systems.

This part of the course strongly relies on a series of homework assignments and on the final project, which all use TRNSYS. Examples of assignments and projects are again available on the accompanying website (see first page). The following paragraph briefly describe a few examples.

Design of solar thermal systems: thermal load, collectors, thermal storage

Generally, the load is provided for assignments and for the project, but for one assignment students are asked to use 2 weeks of measurements from a real site to extrapolate the design load used in a simulation. The importance of sizing the thermal storage in a solar system is shown by various examples. One assignment asks the students to compare the system performance for various collector areas and thermal storage capacities. This is also used to introduced parametric studies in TRNSYS, and student are developing the classical solar fraction vs. collector area and storage volume curves.

Photovoltaic and PV-T systems

The theory of photovoltaic system is covered briefly, the focus being on system-level design and on the interaction with other renewable energy technologies.

Examples of assignments are to design a stand-alone PV-powered system for a bike-sharing company (inspired by the actual systems in Montréal), and to design an off-grid house powered by wind and PV (optimization between the two renewable energy sources and the battery capacity).

Economic Analysis for renewable energy systems

Basics of engineering economic analysis (cash-flow, discounted payback time, internal return rate, etc.) are briefly covered. The concept of levelized life cycle cost is introduced to compare different renewable and non-renewable energy technologies. Economic analysis is typically integrated into the last two homework assignments, while the first ones focus on energy performance only. This is generally combined with exercises asking the students to perform and present energy balances, e.g. through Sankey diagrams.

Concentrating Solar Power and solar cooling

Due to time constraints, these applications, which are less relevant for the Montréal context, are typically covered in a descriptive manner through a lecture presenting the principles and successful applications. These topics generate a significant interest among the students so the possibility of offering optional final project topics is being considered.

Putting it all together: the final project

The final project is intended to be a comprehensive design exercise where students must optimize the performance of their proposed configuration through an economic analysis. The energy performance is defined by the levelized life cycle cost of energy, or specified through targets such reaching a given solar fraction, net-zero energy, or stand-alone operation. Examples of final projects are:

- Design of an SDHW system for a building serving food to homeless people (this project used data from a real project including on-site DHW draw measurements, mechanical room and roof space constraints and local shading). Students were using different weather data, transposing the real site into different contexts.
- Design of a solar combisystem with a 75 % solar fraction for a residential building (students were allowed to select any city and exact location, including local shading).
- Design of a stand-alone polar research station (latitude higher than 75°) powered by solar thermal, PV and wind with a 90 % renewable energy fraction.

One difficulty of the final project is providing detailed feedback to the students, as it is typically due at the end of the exam session. Oral presentations were used during some years but the number of students make it difficult to organize during the last weeks of the term. The project start has been moved earlier in the term (typically before the mid-term exam), and intermediate deliverables are used to provide some feedback.

7. Student feedback and lessons learned

Formal independent surveys (2011 – 2016)

Polytechnique Montréal has a formal assessment program where students fill out anonymous evaluation forms which are collected by an independent school department ("bureau d'appui pédagogique", teaching support group). Professors then receive the compiled evaluation results in the form of percentages of agreement to some 20 questions. Two questions are related to the use of TRNSYS: one on the clarity of homework instructions (it was noticed that complaints were mostly related to difficulties with the TRNSYS files), and one on "equipment, materials, and software". Table 2 shows responses to both questions.

Table 2: Answers to independent student surveys (in % over the 6 years, total number of respondents = 150 over 180 students)

Question	Strongly disagree	Disagree	Agree	Strongly agree
Instructions for homework assignments are clear	0.5 %	4.5 %	45 %	55 %
Equipment, materials, and software used are useful	0 %	0 %	14 %	86 %

In addition to these questions, students are asked to comment on the course in a dedicated space. All answers are again collected by the independent department and then communicated to the instructor. The question is formulated to ask students if they have suggestions to improve the course, but some students use the space to identify the parts that they especially like. The most frequent or relevant comments are summarized below:

- An overwhelming number of students write positive statements on the course as a whole and the fact that it mixes theoretical aspects (the "fundamentals" part) with practical design applications. The fact that these

practical applications are simulation-based design exercises is very often mentioned as a positive point.

- The use of TRNSYS is appreciated, and a few students have suggested also using other programs that would be more likely to be used by consultants.

- Some students have complained that the gap between homework (where "ready-made" TRNSYS projects are provided most often) and the final project (for which students start from a clean sheet) was too large.

- Some students have suggested to spend more time on how to use TRNSYS, or to organize a specific course on the program at the beginning of the term. They have also mentioned that it would help to have more online tutorials available.

- A few students have also suggested increasing the time spent in class using the software (i.e. reducing the lectures). In one extreme case, a student complained about the "fundamentals" part with "equations that we will probably never use in our engineering career", and he/she suggested replacing it with more simulation-based case studies with economic analysis.

- During the years when other programs were used, some students appreciated the mix of programs but many complained that there was not enough time to learn how to use the different programs.

- Over the years, a few students also complained specifically about the place of TRNSYS in the course, and that the course was on simulation rather than on solar energy (2 students over 6 years). One specific comment was that TRNSYS was "irrelevant in the real world", being "much too complicated".

In-class specific survey in 2016

In addition to the formal surveys, the instructor asked some specific questions at the end of the course in 2016. The written survey was anonymous, but answers were collected and processed directly by the instructor. 30 students (over 35) responded to the survey, which had 3 closed questions and was also asking for any other suggestion to improve the course. Table 3 presents the results of the closed questions.

Table 3: Answers to specific student survey in 2016 (in %, total number of respondents = 30 over 35 students)

Question	Strongly disagree	Disagree	Agree	Strongly agree
Simulation-based applications are an important part of the course	0 %	0 %	3 %	97 %
It is a good idea to use TRNSYS, which is flexible and forces users to understand how systems operate, instead of other programs that would be easier to use	0 %	0 %	37 %	63 %
Even if the course is mostly about solar thermal systems, it is a good idea to also cover solar photovoltaic systems and wind energy conversion, even briefly, and to use PV and/or wind in the final project.	0 %	0 %	4 %	96 %

The suggestions to improve the course are summarized below (the numbers in bracket indicate the number of students who made the suggestion). There were 24 comments in total for 30 respondents, and 4 of these comments repeated that TRNSYS was a good tool to understand how systems operate, which was already covered by the second question:

- (5) There should be a separate course (or some periods in the solar class) dedicated to TRNSYS.

- (3) The instructor should provide more explanations on specific TRNSYS components before they are used for the first time in homework or in the project.

- (3) More practical sessions should be devoted to TRNSYS during the course.

- (3) Other easier-to-use programs should be presented as well.

- (3) TRNSYS homework should insist more on creating systems (not just using "pre-canned" systems).

- (2) More TRNSYS tutorials and exercises should be available online.

- (1) TRNSYS documentation should be available in French

Lessons learned

Student feedback has been overwhelmingly positive on the use of TRNSYS, and most students seem satisfied that the course combines theoretical notions (through hand-written exercises and exam) with practical, simulation-based design exercises. The choice of TRNSYS is approved by the vast majority of students, even though they realize that other programs exist which would be easier to use. The second question of the 2016 survey was especially formulated to validate that hypothesis. Some students would like to be exposed to other programs, but they do see value in using a more flexible program even if it is more complicated.

The students generally suggest to spend more time teaching how to use TRNSYS, either in the solar course or in a dedicated training course. They also point at the lack of suitable online examples and tutorials. This illustrates the challenge of teaching solar energy engineering with TRNSYS rather than teaching how to use TRNSYS – it does not seem possible to avoid "software training courses" completely, whether they happen during the class or they are provided elsewhere. The students also indicated a need to evolve more progressively from the first homework assignments, which are very simple and rely on using ready-made projects, to the final project where students must create their system model from scratch. In particular, the difficulty of knowing which components to use and how each component should be used is insufficiently addressed in the present course structure. Again, training material specifically adapted to the course should be developed and provided, either as part of the course material or as online tutorials.

Although not directly indicated by survey answers, anecdotal evidence gained during the attempts to use other programs suggests that the level of comfort and expertise of the instructor with the software is critical to its successful use in teaching. If the instructor uses the program on a regular basis for teaching and research, he/she will know the software limitations and quirks. Even if the problems cannot be fixed, students can be warned about misleading indications, bugs and other problems before they get frustrated with them, which will completely change the dynamics of the exercise. In the author's experience, just quickly trying a few examples before an assignment using a program that is only used once a year for teaching is asking for trouble, even with commercial programs.

8. Conclusions

This paper presents a graduate solar energy engineering course which relies on the TRNSYS simulation tool to engage students in the learning process through design and analysis activities. The course learning objectives are discussed in relation to Bloom's revised taxonomy, showing the role of simulation in reaching the higher levels of objectives. The paper then presents an overview of the course contents, as well as teaching and assessment methods. TRNSYS is used for assignments during the entire teaching term, in order to help students gain confidence in the program and in their skills using it. Some assignments compare hand-calculated values to simulation results to encourage the developments of intuition and skepticism toward simulation results. Student feedback has been overwhelmingly positive on the use of TRNSYS, and on the fact that the course combines theoretical notions (through hand-written exercises and exam) with practical, simulation-based design exercises. Students appreciate the fact that TRNSYS encourages them to think about the design and operation of solar systems before being able to model them, even if they realize that other tools might be easier to use and deliver results faster. Students also point out the lack of training material specific to the subject, which leads to difficulties in selecting and configuring the appropriate TRNSYS components. An accompanying website provides examples of course schedule, assignments and projects.

9. Acknowledgement

10. References

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