


Article

# A Roadmap for the Integration of Active Solar Systems into Buildings

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**Abstract:** This paper aims to simplify the interdisciplinary design process that will be used as a design tool for the viable integration of active solar energy systems into buildings, i.e., Building-Integrated Solar Thermal Systems—BISTSs; Building-Integrated Photovoltaic Systems—BIPVSs, through the creation of a roadmap. The research also aims supplement the work of researchers who have dealt with the creation of design tools that aim to optimise a specific aspect of a building design, or their geometric forms, in order to shape energy-efficient and sustainable architectural solutions. More specifically, a prescriptive design strategy is derived from the proposed design tool. This is based on five design steps, each of which is analysed and which lead to the creation of a comprehensive design tool for siting buildings so as to optimise the integration of solar systems. The originality of this tool is based on the fact that it makes an important step in the standardisation of these studies.

**Keywords:** design guidelines; building integration; roadmap; sustainable development; active solar systems

## 1. Introduction

The first oil crisis in the early 1970s forced the building industry to a sudden awakening, and the development of a concentrated effort, in order to reduce building energy needs, that focused initially on the active systems of the building, with the passive approach to the subject following in the mid-1970s [1]. It is interesting, however, that the reckless use of fossil fuels for energy production that led to the aforementioned environmental problems and oil crisis took place while Europe's average Global Horizontal Irradiance (GHI) was about 1200 kWh/m<sup>2</sup>/year [2]. Considering the above, it became clear that the use and exploitation of renewable energy sources, especially solar energy, during architectural planning is one of the most important parameters a building needs to meet in order to be considered viable. On the other hand, the direction towards solar energy may be the only viable proposition, since it is considered to be the alternative energy source with the greatest potential to reduce the dependence on fossil fuels [3–5].

At the same time, the European Union (EU)'s Climate Action and, in particular, the 20-20-20 program that is currently active, sets targets for a 20% reduction in EU greenhouse gas emissions compared to 1990 levels, for a 20% improvement in the EU's energy efficiency, and for 20% of the EU energy share to be produced from renewable sources [6]. Regarding the post-2020 era, the European Commission has already set new targets for the year 2030, which aim at a 40% reduction in the EU's greenhouse gas emissions compared to 1990 levels, a 27% improvement in the EU's energy efficiency and for 27% of the EU's energy share to be produced from renewable sources [7]. The Commission is also committed by 2050 to reduce its greenhouse gas emissions by 80–95% compared to 1990

levels [7]. Given that buildings are responsible for 40% of the total primary energy needs in the EU [8], the development of effective alternative energy solutions for buildings is imperative. This is complemented by the Energy Performance of Buildings Directive (EPBD) [9], as well as by the Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources [10], which require Renewable Energy Sources (RES) to be actively promoted against the conventional fossil fuels that are used in buildings. The increasing role and incentives given to renewable energy sources through the European legal framework, and the fact that solar energy accounted for the 21.9% of the primary renewables production in 2017 in the southern EU countries [11], mean that Solar Thermal Systems (STs) and Photovoltaics (PVs) will play a key role in buildings, as they contribute directly to their heating and cooling loads, as well as to their supply of electricity and hot water [8]. At the same time, other more specific solar systems, such as polymethylmethacrylate (PMMA) fibers [12] and heliostats for the concentration of solar energy [13], could also contribute in that respect.

Thus, the integration of active solar systems into buildings is coming to the fore, since, according to Hestnes [14], buildings should be able to exploit solar energy for energy generation through the integration of active solar features. This results in an effective contribution to the reduction of energy needs in the building sector, through onsite production of energy [8]. The key role of building-integrated solar active systems in the architectural design of buildings is increasingly becoming evident, especially in countries where high values of annual solar energy are recorded [15,16]. Based on the above, and on the fact that the European Union's legal framework encourages member states to require the use of energy from renewable sources in new and existing buildings [9,10] in their building regulations and codes, several countries have included in their legislation an indirect obligation to integrate active solar energy systems in buildings. For example, the Regulatory Administrative Act 119/2016 [17] of Cyprus requires that at least 25% of the total primary energy that residential buildings consume should come from RES.

However, the participation of building-integrated active solar systems in building design considers additional design parameters. This is because the design and construction of a sustainable, energy-efficient and environmentally friendly building essentially requires a holistic approach to design [18–21]. Specifically, the use of solar energy is one of the key components of the holistic approach to the environmental design issue, which has three prongs: bioclimatic design, the design of energy-efficient structures and the ecological approach to the design. The first two differ in their approach to the subject, since the first deals with passive issues (e.g., geometry, orientation, placements) and the second with energy issues (e.g., energy production). The third tries to deal with the minimisation of the building's ecological footprint [22–24].

All the above demonstrate that the integration of active solar systems into buildings adds various parameters to the architectural design process, thus transforming it into an interdisciplinary field. Particularly, this is analysed with respect to issues related to bioclimatic design and the passive role that active solar systems play in the building, issues that have to do with their active role and are related to their energy production potential and issues that have to do with construction materials and their ecological sensitivity [25]. In this paper, we attempt to simplify this interdisciplinary design process through the creation of a roadmap that can be used as a design tool in the early stages of design.

## 2. Literature Review

The subject of the integration of active solar systems into buildings and research on it is an original application, although not in its entirety. This is because the analysis of a building's construction and the addition of a number of technological systems to it is usual in the contemporary construction industry, since a lot of different systems have been integrated into recent buildings. The research focus in this paper is the integration of active solar systems into buildings and their sustainable operation, since, in their majority of cases, they have not been built for this purpose and their ideal operating

conditions differ, in most cases, from the conditions under which they are called upon to perform, as functional parts of the building shell.

There are already examples of applications where original design process solutions were applied to ensure that the systems would function properly. The integration of such a system in a building requires a modification of the design process in such a way that the integrated system and the building itself can operate in conjunction. The lack of a standardised roadmap for such applications forces design teams to apply their own unique design approach to ensure the system's viability in each case.

Vassiliades [26] studied and presented 43 case studies of buildings with integrated active solar systems. These applications have been extensively analysed separately as well as comparatively. The analysis considered both the buildings and the systems in terms of their type, the type of their integration, their originality, the way they were applied/integrated and the challenges faced therein. Subsequently, various construction issues were illustrated, and aspects of integration according to the demands of each case were highlighted, to present a suggested design strategy for every case.

Considering the above, an investigation shows that the literature on the development of a design tool/roadmap for the integration of active solar systems into buildings is rather limited. In the framework of the aforementioned research, an early attempt was made to create a design/research roadmap, which was based on the research process that was presented in that dissertation. In particular, the investigation started at the urban scale, progressed to the scale of the building and ended with considerations relating to the construction of components making up the shell of the building. The goal was to achieve sustainable building integration by avoiding several passive and technical issues that could affect the efficiency and viability of the systems and of the building itself.

Most of the related work deals with the development of design tools on similar research topics. In the solar urban design field, Lobaccaro et al. [27] and Lobaccaro and Frontini [28] have tried to create design tools that optimise the volume and shape of buildings in existing urban areas to harvest as much insolation as possible and minimise their negative impact on the adjacent lots, whilst Lobaccaro et al. [29] dealt with the estimation of the amount of energy that can be produced from solar envelopes in urban environments. Amado and Poggi [30] promote the energy transition to solar energy in the urban environment using a Geographical Urban Units Delimitation (GUUD) model related to solar potential. The methodology of this research consists of a novel design tool and proposes five steps: an analysis of the urban system, parametric urban modelling, estimation of the solar potential, a forecast of electricity consumption and the application of an urban energy balance. The workflow of the process consists of a combination of geographic information system (GIS) techniques with parametric modelling and analysis of the solar potential.

In the building design field, Attia et al. [31] created a design tool that performs a sensitivity analysis of the possible variations in the design parameters and elements of nearly zero energy buildings (NZEBs) during the early design phases in hot climates, aiming to provide information on the period prior to decision-making for NZEB design. Several researchers have developed design optimisation tools that aim to address specific aspects of building design. Specifically, a number of studies [32–39] have dealt with the creation of design tools that optimise the geometric form of the building and its related components in order to shape energy-efficient and sustainable architecture solutions or to improve the values of specific parameters in the overall design of the building. Related work has also been done for the creation of design optimisation tools that address heating, ventilation and air conditioning (HVAC) system parameters and other similar active energy systems [40–42]. The work of Attia et al. [43] summarises a study undertaken to reveal potential challenges and opportunities for integrating optimisation tools in NZEB design.

The development of design tools and roadmaps is a part of several research and development procedures that aim to optimise related processes in the fields of computing and software architecture [44–46]. At the same time, due to recent strategic shifts away from simply achieving feasibility to achieving optimisation [47], and the benefits obtained by facilities management companies, a process-based approach is well-recognised in the business literature [48,49], and roadmaps for

research and development have been created [47,48,50,51]. Roadmaps in the field of production and manufacturing aim to optimise processes and products [52–56]. Finally, the range of roadmaps that are currently in use is shown in the work of Alturki et al. [57], who propose a structured and detailed design science roadmap to conduct design science research that may be used as a general guide for researchers.

### 2.1. Prototype Systems

There are also examples of research teams that have resolved the construction issues arising from the integration of prototype active solar systems into buildings. In this context, work was done during COST Action TU1205—BISTS [58] by five research teams that developed five different solar systems, the Modular Intergrated Solar/Thermal Flat Plate Collector, the Hybrid Photovoltaic/Solar Thermal (HyPVT), the Concentrating Photovoltaic/Thermal Glazing (CoPVTG), the Solar Plenum and the Trapeze Flat-Plate Solar Thermal Collectors (FPSTC), and proposed viable solutions for building integration (Figure 1). For each system, a specialised design and fabrication solution was adopted that focused on the sustainable operation of both the system and the building.



**Figure 1.** Visualisations of the five systems that were applied to a three-storey building. From the left: the Modular Intergrated Solar/Thermal Flat Plate Collector, the Hybrid Photovoltaic/Solar Thermal (HyPVT), the Concentrating Photovoltaic/Thermal Glazing (CoPVTG), the Solar Plenum and the Trapeze Flat-Plate Solar Thermal Collectors (FPSTC).

### 2.2. Summary of Main Points

The key findings that summarise the main points and limitations of the previous works may be enumerated as follows:

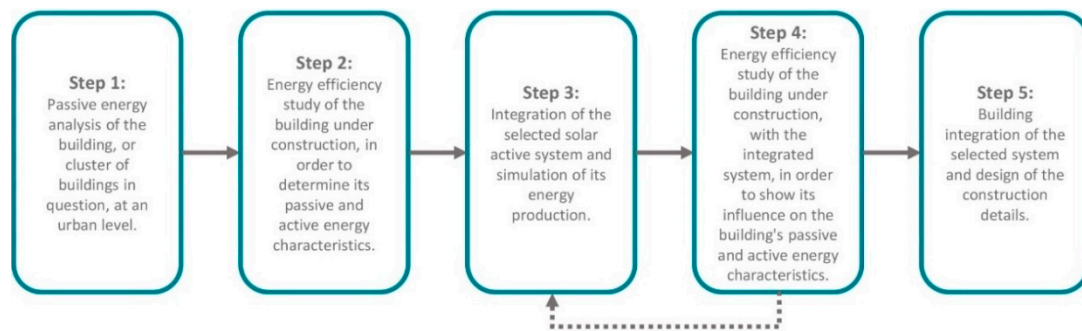
- The current research is focused on the integration of active solar systems into buildings and their sustainable operation, since, in the majority of cases, they have not been built for this purpose.
- The lack of a standardised roadmap forces design teams to apply their own unique design approach for each different case.
- The research team made an early attempt to create a design/research roadmap, which was presented in previous research.
- There have been attempts to develop design tools for similar research topics, which aim to optimise the shape and geometry, or to improve the values of specific parameters in the overall design of buildings and building clusters.
- Design tools and roadmaps can also be encountered in several research and development procedures that aim to optimise related processes in the fields of computing, production, manufacturing and design science research.

## 3. Methodology

In order to become science, novel procedures, such as the proposed roadmap, need to be tested in real conditions, in this case with the application of the proposed methodology to case studies. Since related examples and the literature on the investigation of building-integrated active solar systems are

rather limited [59], in contrast to the corresponding applied methodologies, the proposed methodology was developed based on a literature analysis, and on how the design/research teams in the various case studies designed and integrated the active solar energy systems into model buildings. The research team chose to use these specific research case studies instead of others in the private sector because they were developed under controlled conditions with a very specific methodological course for each case. Specifically, the methodology is an evolution of Vassiliades's research [26] for the development of a novel roadmap. That work was initially based on the collection of relevant literature and on the current state-of-the-art, as well as an analysis of the integration of active solar systems at all design scales, including the urban scale, the building scale and the scale of the unit system. Thus, an early roadmap was developed that proposes a path that a designer may follow for addressing the integration of an active solar system into a building.

In the roadmap above, five design/research steps were proposed, which constitute a design process for achieving a system's integration (Figure 2). The first step is a passive energy analysis of the building, or the cluster of buildings, at an urban level. The aim is to identify the ideal facade or facades within which the active system may be integrated with the least likely propagation of interfering shadows that could affect its performance.



**Figure 2.** The roadmap for the integration of an active solar system into a building.

After selecting the buildings and their related facades, the second step proposes an energy efficiency study of the building under construction or major renovation in order to determine its passive and active energy characteristics. Specifically, the designer must identify the building's needs in terms of transparency, thermal insulation, weather proofing, noise reduction and shading. At the same time, the building's energy needs for heating, cooling, domestic hot water and lighting should also be analysed. This is done so that one is able to select the appropriate active system that may provide the required integration method.

In the third step, a digital model of the building with the integrated system is created, and its energy production is simulated. The aim is to make sure that the appropriate system is chosen and that it can meet the necessary energy needs.

In the fourth step, an energy efficiency study of the building with its integrated system is performed in order to measure its influence on the building's passive and active energy characteristics. If the results are satisfactory, and the system selection is correct, one may proceed to step five, or, in the reverse, one repeats the process from step three until the needs are met.

In the fifth and final step, the designer deals with the integration of the selected system into the building and the configuration of the construction details. These construction details aim to expose possible issues that may be related to the system and have to do with piping, wiring or other technical issues related to each incorporated technology.

Looking back at the practices presented and based on the roadmap above, a common design strategy was derived that was followed in order to form the proposed design tool. This is based on the five steps presented above and aims to create a comprehensive and functional design tool. In addition to the facilitating the design work, thereby saving time and money, the originality of this tool is based

on the fact that it takes an important step in standardising these studies. On the other hand, the implementation of this roadmap by a number of researchers and designers will make cross-referencing possible between different applications, and additionally it will enable us to create a database of buildings with integrated solar systems that could provide designers with options at the front end of the construction and environmental systems detailing process.

It should be noted that, in order for this roadmap to be used, solar energy must have been chosen as the main renewable energy source of the building, and the use of a building-integrated active solar system must also have been chosen. Otherwise, the methodological process may be very different, since it will follow the characteristics and requirements of each case.

#### 4. Roadmap Development

As was mentioned in the methodology section, the full development of the roadmap is performed by analysing each step based on the work done by other researchers and the full development of the process that needs to be followed at each step.

##### 4.1. Step 1—Passive Analysis

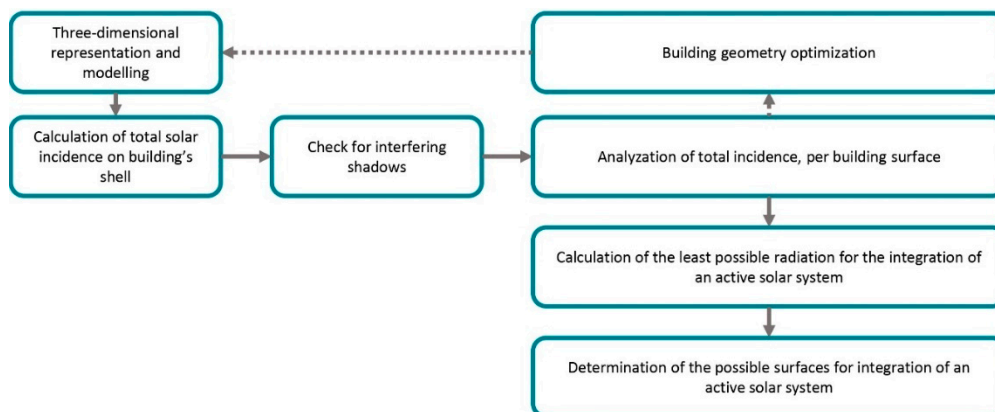
Step 1 of the roadmap deals with the passive energy analysis of the building, or cluster of buildings, at an urban level. The process is based on previous work by Savvides et al. [60,61], and starts with the three-dimensional representation and modelling of the building, or building cluster, at an urban level. This model is used for simulations that should be made in order to calculate the solar incidence on a building's shell. The total insolation value represents a first attempt to quantify the building's solar potential, while the three-dimensional model can also provide an accurate estimation of any interfering shadows that could affect the building's solar performance.

Subsequently, the incident radiation on a building's shell is thoroughly analysed, which provides a first indication of the surfaces on which an active solar system could be viably integrated in terms of energy production. It also an early attempt to identify which surfaces of a building might require passive solar protection to avoid possible overheating issues. All the above help in the initial optimisation of a building's geometry.

At the same time, because incident radiation may not be used on its own to fully determine the viability of a building to reasonably accept the integration of an active solar system, the least possible amount of incident radiation on a surface that would allow for this should be calculated. Vassiliades [26] reports that a building may exhibit a high value for average incident radiation, but a number of its constituent facades might exhibit comparatively lower incidence values, rendering the integration of an active solar system non-viable, a fact exhibited by an equation that provides the lowest radiation needed for a viable integration of an active solar system on a surface. The parameters for that figure's calculation is the system's performance, the energy cost in euros per kWh, the years for repayment and the system installation cost in euros per square meter of installation. The equation is presented below:

$$\text{Radiation} \left( \frac{\text{kWh}}{\text{m}^2} \right) = \frac{\text{System Installation and Maintenance Cost} \left( \frac{\text{€}}{\text{m}^2} \right)}{\text{System Performance} \times \text{Energy Cost} \left( \frac{\text{€}}{\text{kWh}} \right) \times \text{Years for Repayment}}. \quad (1)$$

The first methodological step of the roadmap described above is presented in Figure 3.



**Figure 3.** The basic methodological steps for the first step of the roadmap, which deals with the passive energy analysis of the building, or cluster of buildings, at an urban level.

#### 4.2. Step 2—Energy Efficiency Study

Step 2 of the roadmap deals with the energy efficiency study of the building under construction in order to determine its passive and active energy characteristics. The process starts with the analysis and determination of the thermal insulation, weather proofing and noise reduction requirements and characteristics of the building. These characteristics need to be defined because they could have an impact on the choice of the active solar system to be integrated into the building.

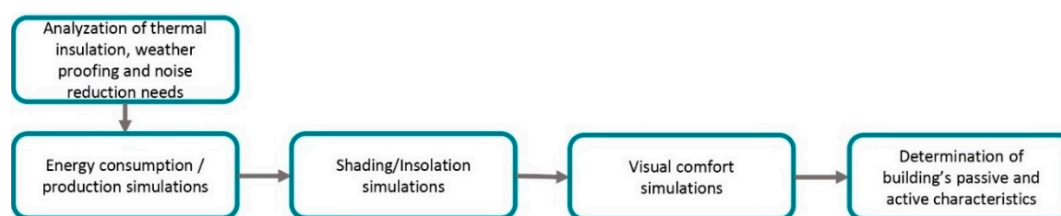
Subsequently, several simulations are performed to determine several quantitative characteristics of the building, such as the energy needs of the building and, specifically, its needs for heating, cooling, lighting and domestic hot water. Any possible energy production by nonintegrated active systems is also simulated at this stage in order to determine the energy balance of the building.

Shading and insolation of the building’s envelope, and especially of its glazed surfaces, is then simulated since they significantly contribute to the thermal performance of the building. This evaluation could be achieved through the use of shading masks.

A visual comfort analysis follows, since it is an essential parameter of human comfort, while it may also be defined as a subjective condition of well-being in an indoor built environment [62]. It is used to investigate visual comfort of the occupants in terms of natural lighting and glare issues [63] as well as in terms of visual connection with the exterior environment.

The methodology that is followed in this step has been extensively presented by Vassiliades et al. [25], and aims at the determination of the passive and active characteristics of the building that affect the choice of the active solar system.

The second methodological step of the roadmap described above is presented in Figure 4.



**Figure 4.** The basic methodological steps for the second step of the roadmap, which deals with the energy efficiency study of the building under construction.

#### 4.3. Step 3—Integration of an Active System

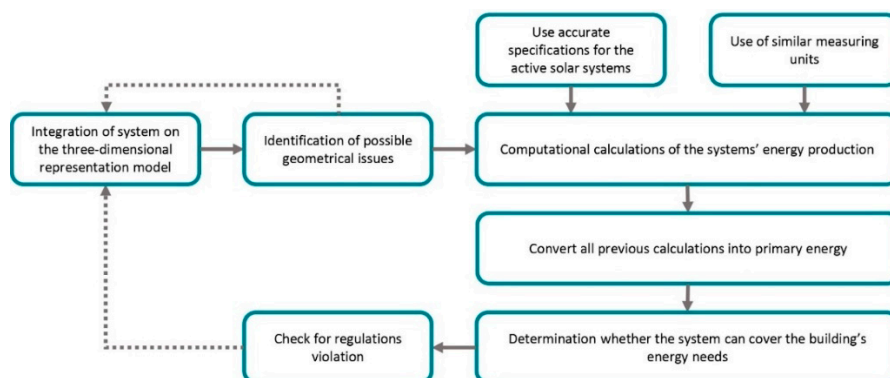
Step 3 of the roadmap deals with the integration of a selected active solar system and a simulation of its energy production in order to confirm that it may cover the energy needs of the building and has the expected passive behavior as determined in Step 2. The process starts with the integration of a system on a three-dimensional model of a building to identify possible geometrical as well as morphological issues that may be optimised at this early stage.

Subsequently, the computational calculations of a system's energy production are performed using appropriate software. The software can be selected by the designer as per the requirements of the project. However, it is important to confirm the validity of the simulation results by performing pilot simulations using a well-established software, e.g., TRNSYS [64].

In order to obtain accurate results, it is important to use the technical characteristics of the specific models of used active solar systems. It should also be noted that, for evaluation purposes, the energy production of all used systems should be given in the same unit notations. Similarly, all of the energy production and consumption values should be converted into primary energy values following the energy performance of buildings Directive (2018/844/EU) [9] in order to allow for comparability between buildings and help facilitate their subsequent certification. Similar work that calculates the energy production of building-integrated active solar systems via computational simulations has been performed by Vassiliades et al. [25,26,65,66].

Finally, any chosen design should be implemented without violating applicable regulations.

The third methodological step of the roadmap described above is presented in Figure 5.



**Figure 5.** The basic methodological steps for the third step of the roadmap, which deals with the integration of the selected active solar system and the simulation of its energy production.

#### 4.4. Step 4—Energy Efficiency Study Subsequent to System Integration

Step 4 of the roadmap deals with the energy efficiency study of the building under construction, with the integrated system, in order to show its influence on the building's passive and active energy characteristics. The process is very similar to Step 2 of the roadmap. Specifically, the energy requirements and the energy production of a building are simulated in order to determine the energy balance of said building, followed by shading and insolation simulations and a visual comfort analysis with the use of the same methodological process as in Step 2. The difference in this step is that, if the results of the simulations are not as expected, the designer may return to Step 3 and try a different system.

The fourth methodological step of the roadmap is presented in Figure 6.





**Figure 6.** The basic methodological steps for the fourth step of the roadmap, which deals with the energy efficiency study of the building under construction, with the integrated system.

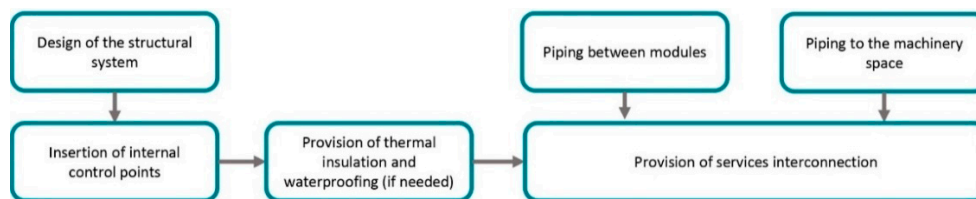
4.5. Step 5—Integration of the Selected System into the Building

Step 5 of the roadmap deals with the integration of the selected system into the building and the configuration of construction details. The process starts with the design of the structural system for the support of the solar system. Subsequently, internal control points may be placed in selected interior locations, from which visual inspections and repairs to piping connections may be made.

After that, depending on the integrated system and the possibility of the need for weather protection, the continuity of the system array should be ensured in order to provide the desired thermal insulation and waterproofing.

Regarding connection to technical services (electromechanical and water supply), the connectedness to the system’s modules should be anticipated. With regard to piping between two modules that are placed at a distance from service outlets emanating from a mechanical room, these should be integrated using through-wall connections.

The fifth methodological step of the roadmap is presented in Figure 7.



**Figure 7.** The basic methodological steps for the fifth step of the roadmap, which deals with the integration of the selected system into the building and design of the construction details.

4.6. Formulation of a Complete Roadmap

Based on the early roadmap that was presented above, and in combination with extensive analysis at each step, a complete roadmap was created and is shown in Figure 8. The development of this design methodology may be followed by designers for the integration of active solar systems into buildings. Moving from step to step, the designer may apply the proposed methodology to integrate a solar system within new or existing buildings. It should be noted that the roadmap is a general methodology that may be applied in the majority of cases. However, it is at the discretion of each designer to apply it accordingly and to use it based on the specific circumstances that apply in each case.

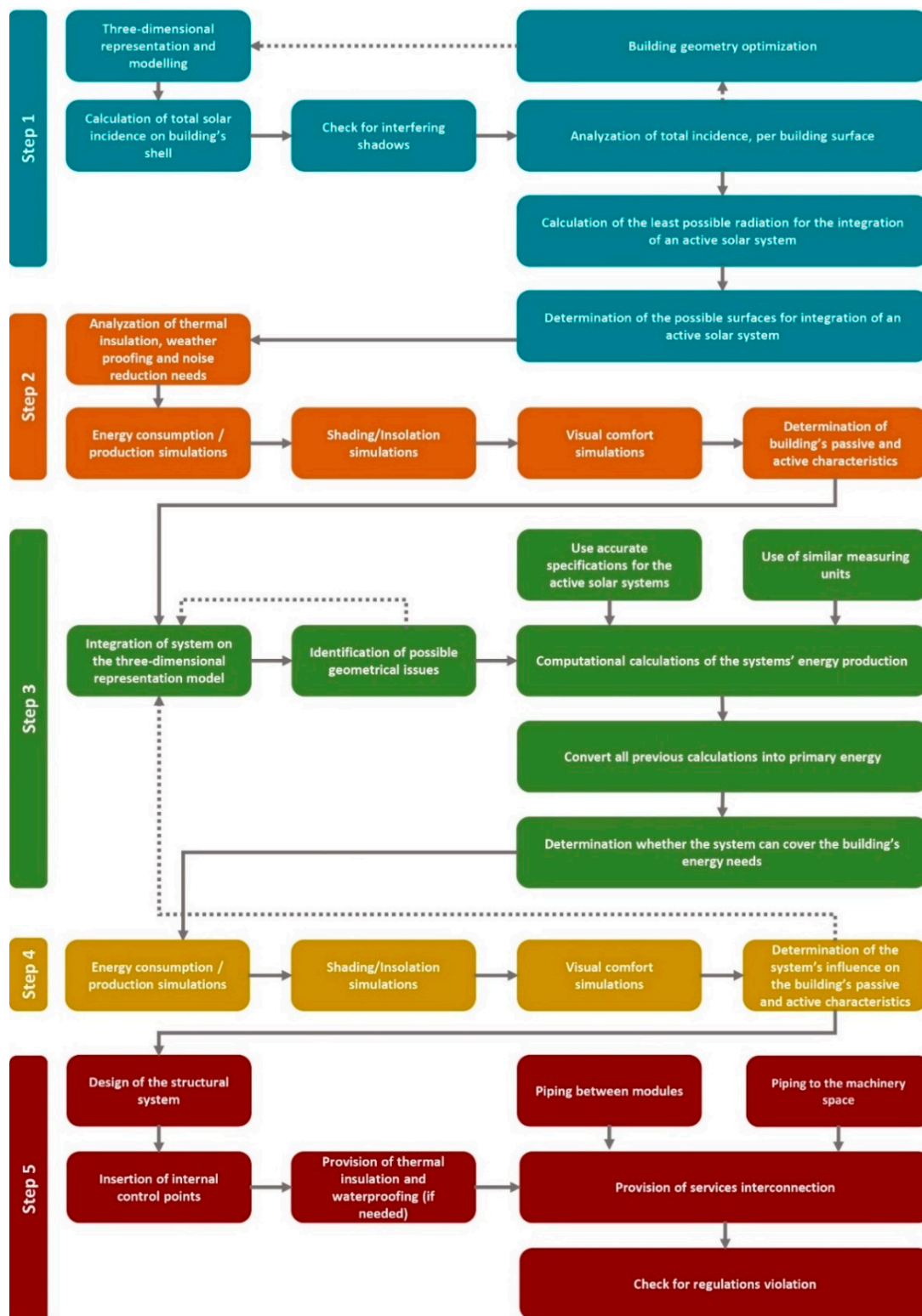


Figure 8. Illustration of the proposed methodology for a roadmap pertaining to the integration of active solar systems into buildings.

### 5. Discussion and Conclusions

The main aim of this research is to create a roadmap that proposes a design path that a designer may follow to integrate an active solar system into a building. The research is based on the work of Vassiliades [26], which represents an early attempt to create a roadmap to ensure the viability of

building-integrated active solar systems. In order to achieve this, a methodological procedure was developed as an extension to the aforementioned roadmap.

Given that contemporary architectural and urban design strategies with regard to buildings and building clusters aim to achieve the smallest possible energy consumption, challenges arise from the potential for local energy production, which depends on the use of renewable energy, and is interpreted as solar energy in a number of countries in the EU, since it accounted for 6.4% of the primary renewables production in 2017 for the EU-28 and 21.9% of the primary renewables production in 2017 for the southern EU countries [11]. This is because the main driver of energy consumption in buildings is thermal comfort for users; an example of this is the fact that 49% of the total household energy consumption in the United States in 2005 came from space heating and cooling loads [67]. This is because energy demand for climate control and the level of indoor environmental comfort that is achieved are interrelated, such that a higher level of thermal comfort demands higher energy consumption and vice versa [68]. This may be balanced in a nearly zero energy building given an appropriate study of the building's thermal comfort requirements and potential energy loads, which will lead to an appropriate selection of the type and size of the renewable system. Given that solar energy is the renewable energy that was chosen to cover the building's energy needs, the presented research aims to simplify and standardise the process of integrating an active solar system into a building in order to ensure that its energy and environmental behaviour complies with legislation and good sustainable urban and building design practices.

The originality of this research is based on the fact that, although a number of other design tools/roadmaps can be found in the literature, none of them focuses on building integration. At the same time, the research complements the work and findings of other researchers on the subject [26–30], since it focuses on the sustainable use of building-integrated active solar systems in terms of their energy production potential. Specifically, the proposed toolset, which optimises a building's massing to harvest as much insolation as possible and promotes electricity production by the application of solar energy, is highly supplemented by the proposed roadmap, given that, in Step 1, the passive energy analysis of the building, or cluster of buildings, aims to confirm the ideal façade orientation for sustainable integration of active solar systems, and also aims to confirm that the selected massing configuration results in the least likely propagation of interfering shadows that could affect its performance. At the same time, Steps 2–4 deal with the active and passive behavior of the building's energy and environmental control performance, as well as with its energy production potential, which are dependent on its massing configuration.

The research also supplements the work of researchers who have dealt with the creation of design tools that aim to optimise a specific aspect of a building design, or their geometric forms, in order to shape energy-efficient and sustainable architectural solutions [31–38]. This is demonstrated in Step 1 of the methodology, where an initial optimisation of the building's geometry is proposed. A second prompt for the optimisation of the building's geometry is referred to in Step 3 of the roadmap subsequent to the system's integration into the building, and helps to identify possible geometrical issues that could be regulated at that point. Similarly, Steps 2–4 of the proposed roadmap, which outline the energy efficiency studies to be performed before and after the integration of the system, extend and improve the work of researchers that have proposed design optimisation tools [40–43]. The final step of the roadmap focuses on that aspect, since it deals with the integration of the selected system into the building and the configuration of the construction details, aiming at the system's viable and seamless operation.

At the same time, it should be noted that, despite the difference in the subject between this research and the work of other researchers [44–48,50,52–55] dealing with the development of roadmaps for the optimisation of related processes in the field of research and development and in the field of production and manufacturing, the work presented in this paper contributes to the wider field of technology as it proposes a standardisation process that relies on a variety of parameters that need to be approached in an interdisciplinary way by several different professionals and researchers. Thus, it contributes to the

minimisation of the study time needed for this kind of application by minimising the economic cost, confirming the contribution to sustainability of the integration of such systems into buildings, and reducing the risk of a potential investment in this type of building.

The implementation of the roadmap also resolves issues and speeds up potential research work. Particularly, it was observed that, in the work done by COST Action TU1205—BISTS [58], where five research teams developed five different solar systems and proposed viable solutions for their integration into a building, each team applied a different and specialised design and manufacturing solution for each system. With the use of the roadmap in similar research works, the process is expected to be completed more quickly given that teams may focus on the performance of the system itself and not on the investigation of building integration processes, since this will be fundamentally resolved by the roadmap.

However, in order to implement the roadmap, there is a need for researchers to take a common approach and use common units of measurement, as described in the third step of the methodology. It should further be noted that the implementation of the roadmap by a number of researchers and designers will make possible cross-referencing of the results between different applications and case studies, thereby leading to the creation of a database of buildings with integrated active solar systems. This database can then provide researchers and designers with an early picture of the choices they can make in their own studies and applications.

#### *Further Research*

Based on the current research, and with the creation and constant update of the aforementioned database, this roadmap could evolve into a more detailed tool that could provide further information to designers with the presentation of a comparative analysis and data for each design step, which may be based on corresponding design applications in the database. Furthermore, other possible research directions may entail the digitisation of the roadmap and the integration of computational processes in it, within which the designer may insert additional parameters that produce results without the need to use independent computing processes and software. Further research could recheck the roadmap and redefine its steps and parameters based on data and feedback from the implementation of this process in realised projects.

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#### **Abbreviations**

BISTS	Building Integrated Solar Thermal Systems
BIPVS	Building Integrated Photovoltaic Systems
GHI	Global Horizontal Irradiance
EU	European Union
EPBD	Energy Performance of Buildings Directive
RES	Renewable Energy Sources
STS	Solar Thermal Systems
PV	Photovoltaics
PMMA	Polymethylmethacrylate
GUUD	Geographical Urban Units Delimitation
GIS	Geographic Information Systems
NZEB	Nearly Zero Energy Buildings
HVAC	Heating, ventilation, and air conditioning
HyPVT	Hybrid Photovoltaic/Solar Thermal
CoPVTG	Concentrating Photovoltaic/Thermal Glazing
FPSTC	Flat-plate Solar Thermal Collectors

## References

1. Tombazis, A.N. Architectural design: A multifaceted approach. *Renew. Energy* **1994**, *5*, 893–899. [CrossRef]
2. Technology Roadmap, Solar Photovoltaic Energy. *Int. Energy Agency* **2014**, *58*. Available online: [https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy\\_2014edition.pdf](https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf) (accessed on 1 June 2015).
3. Yang, Y.; Wang, Q.; Xiu, D.; Zhao, Z.; Sun, Q. A building integrated solar collector: All-ceramic solar collector. *Energy Build.* **2013**, *62*, 15–17. [CrossRef]
4. Koroneos, C.; Spachos, T.; Moussiopoulos, N. Exergy analysis of renewable energy sources. *Renew. Energy* **2003**, *28*, 295–310. [CrossRef]
5. Painuly, J. Barriers to renewable energy penetration; a framework for analysis. *Renew. Energy* **2001**, *24*, 73–89. [CrossRef]
6. The 2020 Climate and Energy Package. European Commission Climate Action. 2009. Available online: [http://ec.europa.eu/clima/policies/package/index\\_en.htm](http://ec.europa.eu/clima/policies/package/index_en.htm) (accessed on 1 June 2015).
7. Climate Action. 2014. Available online: [https://europa.eu/european-union/topics/climate-action\\_en](https://europa.eu/european-union/topics/climate-action_en) (accessed on 26 April 2018).
8. Kalogirou, S.A. Building integration of solar renewable energy systems towards zero or nearly zero energy buildings. *Int. J. Low Carbon Technol.* **2013**, *10*, 379–385. [CrossRef]
9. *Energy Performance of Buildings Directive (2018/844/EU)*; EU: Brussels, Belgium, 2018; pp. 75–91.
10. Directive (EU) 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources, 2018AD. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001> (accessed on 2 May 2019).
11. Renewable Energy Statistics, Eurostat. 2019. Available online: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable\\_energy\\_statistics#Wind\\_power\\_becomes\\_the\\_most\\_important\\_renewable\\_source\\_of\\_electricity](https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics#Wind_power_becomes_the_most_important_renewable_source_of_electricity) (accessed on 15 March 2019).
12. Song, J.; Zhu, Y.; Tong, K.; Yang, Y.; Reyes-Belmonte, M.A. A note on the optic characteristics of daylighting system via PMMA fibers. *Sol. Energy* **2016**, *136*, 32–34. [CrossRef]
13. González-Pardo, A.; Cesar Chapa, S.; Gonzalez-Aguilar, J.; Romero, M. Optical performance of vertical heliostat fields integrated in building façades for concentrating solar energy uses. *Sol. Energy* **2013**, *97*, 447–459. [CrossRef]
14. Hestnes, A.G. Building Integration Of Solar Energy Systems. *Sol. Energy* **1999**, *67*, 181–187. [CrossRef]
15. Bougiatioti, F.; Michael, A. The architectural integration of active solar systems. Building applications in the Eastern Mediterranean region. *Renew. Sustain. Energy Rev.* **2015**, *47*, 966–982. [CrossRef]
16. Michael, A.; Bougiatioti, F.; Oikonomou, A. Less Could Be More: Architectural Integration of Active Solar Systems in Existing Urban Centres. In Proceedings of the 7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010), Aghia Napa, Cyprus, 7–10 November 2010; IET: Rautistrasse, Zürich, 2011.
17. K.Δ.Π. 119/2016. The Laws that Regulate the Energy Efficiency of Buildings, Cyprus. 2016. Available online: <http://www.cea.org.cy/wp-content/uploads/2017/01/kdp-119-2016.pdf> (accessed on 18 April 2018).
18. Hagemann, I.B. Solar Design in Architecture and Urban planning. In Proceedings of the Urban Planning-Sustainable Cities, Tokyo, Japan, 2005; pp. 1–10.
19. Vale, B.; Vale, R. *Green Architecture: Design for a Sustainable Future*; Thames & Hudson Ltd.: London, UK, 1991; ISBN 978-0500341179.
20. Philokyprou, M.; Savvides, A.; Michael, A.; Malaktou, E. Examination and assessment of the environmental characteristics of vernacular rural settlements. Three case studies in Cyprus. In Proceedings of the 5th International Conference on Vernacular Heritage, Sustainability and Earthen Architecture, Valencia, Spain, 11–13 September 2014; Taylor & Francis Group: Didcot, UK, 2014; pp. 613–618.
21. Knudstrup, M.-A.; Ring Hansen, H.T.; Brunsgaard, C. Approaches to the design of sustainable housing with low CO<sub>2</sub> emission in Denmark. *Renew. Energy* **2009**, *34*, 2007–2015. [CrossRef]
22. Michael, A.; Phocas, M. Construction Design and Sustainability in Architecture: Integrating Environmental Education into Architectural Studies. *J. Renew. Energy Power Q.* **2012**, 190–195. [CrossRef]
23. Phocas, M.; Michael, A.; Fokaides, P. Integrated Interdisciplinary Design: The Environment as Part of Architectural Education. *Renew. Energy Power Q. J.* **2011**, *9*, 937–941. [CrossRef]

24. Hui, S.C. Low energy building design in high density urban cities. *Renew. Energy* **2001**, *24*, 627–640. [CrossRef]
25. Vassiliades, C.; Michael, A.; Savvides, A.; Kalogirou, S. Improvement of passive behaviour of existing buildings through the integration of active solar energy systems. *Energy* **2018**, *163*, 1178–1192. [CrossRef]
26. Vassiliades, C. Building Integration of Active Solar Systems: Addressing all Scales of Intervention and Ensuring their Active and Passive Integration Viability in the Eastern Mediterranean Region. Ph.D. Thesis, University of Cyprus, Nicosia, Cyprus, 2018.
27. Lobaccaro, G.; Frontini, F.; Masera, G.; Poli, T. SolarPW: A New Solar Design Tool to Exploit Solar Potential in Existing Urban Areas. *Energy Procedia* **2012**, *30*, 1173–1183. [CrossRef]
28. Lobaccaro, G.; Frontini, F. Solar Energy in Urban Environment: How Urban Densification Affects Existing Buildings. *Energy Procedia* **2014**, *48*, 1559–1569. [CrossRef]
29. Lobaccaro, G.; Fiorito, F.; Masera, G.; Poli, T. District geometry simulation: A study for the optimization of solar facades in urban canopy layers. *Energy Procedia* **2012**, *30*, 1163–1172. [CrossRef]
30. Amado, M.; Poggi, F. Solar urban planning: A parametric approach. *Energy Procedia* **2014**, *48*, 539–1548. [CrossRef]
31. Attia, S.; Gratia, E.; De Herde, A.; Hensen, J.L.M. Simulation-based decision support tool for early stages of zero-energy building design. *Energy Build.* **2012**, *49*, 2–15. [CrossRef]
32. Caldas, L.G.; Norford, L.K. A design optimization tool based on a genetic algorithm. *Autom. Constr.* **2002**, *11*, 173–184. [CrossRef]
33. Turrin, M.; von Buelow, P.; Stouffs, R. Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *Adv. Eng. Inf.* **2011**, *25*, 656–675. [CrossRef]
34. Caldas, L. GENE\_ARCH: An Evolution-Based Generative Design System for Sustainable Architecture. In *Intelligent Computing in Engineering and Architecture-EG-ICE 2006*; Smith, I.F.C., Ed.; Springer: Berlin/Heidelberg, Germany, 2006; pp. 109–118.
35. Kämpf, J.H.; Robinson, D. Optimisation of building form for solar energy utilisation using constrained evolutionary algorithms. *Energy Build.* **2010**, *42*, 807–814. [CrossRef]
36. Charron, R.; Athienitis, A. The Use of Genetic Algorithms for a Net-Zero Energy Solar Home Design Optimisation Tool. In Proceedings of the PLEA2006, Geneva, Switzerland, 6–8 September 2006. Available online: <https://www.researchgate.net/publication/241734123> (accessed on 11 October 2018).
37. Østergård, T.; Jensen, R.L.; Maagaard, S.E. Building simulations supporting decision making in early design—A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 187–201. [CrossRef]
38. Wang, W.; Rivard, H.; Zmeureanu, R. Floor shape optimization for green building design. *Adv. Eng. Inf.* **2006**, *20*, 363–378. [CrossRef]
39. Vallet, F.; Eynard, B.; Millet, D.; Mahut, S.G.; Tyl, B.; Bertoluci, G. Using eco-design tools: An overview of experts' practices. *Des. Stud.* **2013**, *34*, 345–377. [CrossRef]
40. Huang, W.; Lam, H.N. Using genetic algorithms to optimize controller parameters for HVAC systems. *Energy Build.* **1997**, *26*, 277–282. [CrossRef]
41. Granlund, M.P.; Hasan, A.; Sirén, K.; Palonen, M.; Siren, K. A Genetic Algorithm for Optimization of Building Envelope and HVAC System Parameters. In Proceedings of the Eleventh International IBPSA Conference, Glasgow, Scotland, 27–30 July 2009. Available online: <https://www.researchgate.net/publication/252429941> (accessed on 11 October 2018).
42. Hamdy, M.; Hasan, A.; Siren, K. Optimum design of a house and its HVAC systems using simulation-based optimisation. *Int. J. Low Carbon Technol.* **2010**, *5*, 120–124. [CrossRef]
43. Attia, S.; Hamdy, M.; O'Brien, W.; Carlucci, S. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy Build.* **2013**, *60*, 110–124. [CrossRef]
44. Garlan, D. Software Architecture: A Roadmap, Pittsburgh. 2000. Available online: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.571.8735&rep=rep1&type=pdf> (accessed on 11 October 2018).
45. Srinivasan, M.K.; Sarukesi, K.; Keshava, A.; Revathy, P. *eCloudIDS—Design Roadmap for the Architecture of Next-Generation Hybrid Two-Tier Expert Engine-Based IDS for Cloud Computing Environment*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 358–371.
46. Jennings, N.R.; Wooldridge, M. A Roadmap of Agent Research and Development. *Auton. Agents Multi-Agent Syst.* **1998**, *1*, 7–38. Available online: <https://link.springer.com/content/pdf/10.1023/A:1010090405266.pdf> (accessed on 11 October 2018). [CrossRef]

47. *Embedded Systems Design: The ARTIST Roadmap for Research and Development*; Bouyssounouse, B.; Sifakis, J. (Eds.) Springer: Berlin/Heidelberg, Germany, 2005; ISBN 9783540319733.
48. Corallo, A.; Margherita, A.; Scalvenzi, M.; Storelli, D. Building a process-based organization: The design roadmap at Superjet International. *Knowl. Process Manag.* **2010**, *17*, 49–61. [[CrossRef](#)]
49. Kim, K.; Lee, K. Collaborative product design processes of industrial design and engineering design in consumer product companies. *Des. Stud.* **2016**, *46*, 226–260. [[CrossRef](#)]
50. Daim, T.U.; Oliver, T. Implementing technology roadmap process in the energy services sector: A case study of a government agency. *Technol. Forecast. Soc. Chang.* **2008**, *75*, 687–720. [[CrossRef](#)]
51. Lu, H.; You, H.; Lu, H.; You, H. Roadmap Modeling and Assessment Approach for Defense Technology System of Systems. *Appl. Sci.* **2018**, *8*, 908. [[CrossRef](#)]
52. Frazier, F.W.E. Direct Digital Manufacturing of Metallic Components: Vision and Roadmap. In Proceedings of the 21st International Solid Freeform Fabrication Symposium, Austin, TX, USA, 9–11 August 2010; pp. 9–11. Available online: <http://sffsymposium.engr.utexas.edu/Manuscripts/2010/2010-60-Frazier.pdf> (accessed on 11 October 2018).
53. Putnik, G.; Sluga, A.; ElMaraghy, H.; Teti, R.; Koren, Y.; Tolio, T.; Hon, B. Scalability in manufacturing systems design and operation: State-of-the-art and future developments roadmap. *CIRP Ann.* **2013**, *62*, 751–774. [[CrossRef](#)]
54. Tate, D.; Nordlund, M. A Design Process Roadmap as a General Tool for Structuring and Supporting Design Activities. In Proceedings of the Second World Conference Integrated Design & Process Technology (IDPT-Vol. 3), Society for Design and Process Science, Austin, Texas, 1–4 December 1996; pp. 97–104. Available online: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.473.8676&rep=rep1&type=pdf> (accessed on 11 October 2018).
55. Martin-Moe, S.; Lim, F.J.; Wong, R.L.; Sreedhara, A.; Sundaram, J.; Sane, S.U. A new roadmap for biopharmaceutical drug product development: Integrating development, validation, and quality by design. *J. Pharm. Sci.* **2011**, *100*, 3031–3043. [[CrossRef](#)]
56. Zhang, Z.; Ou, J.; Li, D.; Zhang, S.; Zhang, Z.; Ou, J.; Li, D.; Zhang, S. Optimization Design of Coupling Beam Metal Damper in Shear Wall Structures. *Appl. Sci.* **2017**, *7*, 137. [[CrossRef](#)]
57. Alturki, A.; Gable, G.G.; Bandara, W. A Design Science Research Roadmap. In Proceedings of the International Conference on Design Science Research in Information Systems, Milwaukee, WI, USA, 5–6 May 2011; Springer: Berlin/Heidelberg, Germany, 2011; pp. 107–123. Available online: <https://eprints.qut.edu.au/42496/7/42496.pdf> (accessed on 11 October 2018).
58. Kalogirou, S.A.; Palombo, A.; Pugsley, A.; Zacharopoulos, A.; Besheer, A.; Krstic-Furundzic, A.; Enesca, A.; Duță, A.; Savvides, A.; Ford, A.; et al. *Building Integrated Solar Thermal Systems, Design and Applications Handbook*; Kalogirou, S.A., Ed.; COST Office: Brussels, Belgium, 2017; ISBN 978-9963-697-22-9.
59. Li, L.; Qu, M.; Peng, S. Performance evaluation of building integrated solar thermal shading system: Building energy consumption and daylight provision. *Energy Build.* **2016**, *113*, 189–201. [[CrossRef](#)]
60. Savvides, A.; Vassiliades, C.; Michael, A. Geometrical Optimization of the Urban Fabric in order to Ensure the Viability of Building Integration of Active Solar Systems. In Proceedings of the First International Conference on Building Integrated Renewable Energy Systems, Dublin, Ireland, 6–9 March 2017; Kalogirou, S., Kennedy, D., Eds.; p. 12.
61. Savvides, A.; Vassiliades, C.; Michael, A.; Kalogirou, S. Siting and building-massing considerations for the urban integration of active solar energy systems. *Renew. Energy* **2019**, *135*, 963–974. [[CrossRef](#)]
62. *Light and lighting—Basic Terms and Criteria for Specifying Lighting Requirements*; EN 12665: Brussels, Belgium, 2011; pp. 3–48.
63. Carlucci, S.; Causone, F.; De Rosa, F.; Pagliano, L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renew. Sustain. Energy Rev.* **2015**, *47*, 1016–1033. [[CrossRef](#)]
64. TRNRSYS. 2019. Available online: <http://www.trnsys.com/> (accessed on 04 May 2019).
65. Vassiliades, C.; Savvides, A.; Michael, A. Investigation of Sun Protection Issues of Building Envelopes via Active Energy Production Systems. In Proceedings of the Euro Elecs 2015, Guimarães, Portugal, 21–23 July 2015; Bragança, L., Yuba, A.N., Engel de Alvarez, C., Eds.; pp. 697–706.

66. Vassiliades, C.; Michael, A.; Savvides, A.; Kalogirou, S. Environmental Assessment of the Integration of Active Solar Energy Systems on Building Envelopes in Southern Europe. In Proceedings of the 10th International Conference on Sustainable Energy and Environmental Protection (SEEP 2017), Bled, Slovenia, 27–30 June 2017; Kropf, J., Olabi, A.G., Goričanec, D., Božičnik, S., Eds.; University of Maribor Press: Bled, Slovenia, 2017; pp. 179–190.
67. Seiferlein, K.E. *Annual Energy Review 2007*; USDOE Energy Information Administration (EIA): Washington, DC, USA, 2008. [[CrossRef](#)]
68. Simmonds, P. Thermal Comfort and Optimal Energy Use. *ASHRAE Trans.* **1993**, *99*, 1037–1048.



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