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An Image-based Analysis of Solar Radiation for Urban Settings

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Abstract

This paper describes a novel approach for evaluating the total annual/monthly irradiance incident on building facades in urban settings. The analysis is founded on a physically-based rendering approach and uses data-visualisation techniques to generate 'maps' (i.e. false-colour images) of annual/monthly irradiance. The irradiance 'maps' are derived from hourly time-series data for one year and take accurate account of shading by, and inter-reflection from, other buildings and surfaces. The sun and sky irradiance are evaluated separately. The sky contribution is calculated using realistic, non-isotropic models for the sky radiance distribution. The 'maps' can be used to confidently identify facade-locations where there is high irradiance, for example to aid the siting of photo-voltaic panels. The technique can be applied to scenes of arbitrary complexity from a single building to fully 'worked-up' city models. The results of the analysis have been linked to a GIS-based solar energy planning system. The system is targeted at city planners and one of its aims is to encourage the consideration of solar energy in the urban planning process.

INTRODUCTION

Building Integrated Photovoltaics

Government agencies throughout the developed world have created initiatives to promote the research, development and uptake of electricity generation by photovoltaics (PVs) [1]. Schemes such as the 'Million solar rooftops' (USA) and the 'European 500,000 PV' are creating a substantial market for photovoltaic technologies [2]. The most common PV devices at present are based on silicon in various formulations, e.g. monocrystalline, polycrystalline and amorphous. New materials and novel approaches to PV fabrication are being investigated. Whatever the type of the PV module, its output is dependent primarily on the incident solar radiation.

The annual-total irradiance on a surface depends on the geographical location, the prevailing meteorological conditions, the orientation of the surface and the local environment. If shading of the surface is not an issue, then the effect of the local environment can be largely ignored and the annual-total irradiance can be reliably estimated from pre-calculated values [3]. This is often the case for most of the domestic PV installations where the panels are attached to sloping roofs that experience little or no shading.

PV installations have also been demonstrated in cities [3]. Here, the economics of PV can be made more attractive by using the PV panels both as a construction material and as a source of electricity. Hence the term building integrated photovoltaics or BIPV. Prestige buildings such as 4 Times Square (New York, USA) exemplify this technique [4]. In cities, most building facades will experience some shading and the local environment must be considered in any evaluation of the available irradiance. Urban BIPV is an emerging application area for PV, and the investment needed for each installation can be considerable. Consequently, the wider adoption of BIPV will depend on sound demonstrations of its economic viability.

Foremost in the evaluation of PV economics where shading is a factor is the calculation of the available solar energy. The computation of irradiance in complex urban environments - where shading in an inevitable consequence of the building form - is the subject of this paper.

Irradiance prediction: Existing approaches

Several different approaches to the problem of irradiance prediction in shaded environments have been described in the literature. Notable examples include: a simulation-based approach [5]; a manual projection-based method [6] and a computer-based projection method [7]. Any of these can predict the annual total irradiance at a point using various modelling assumptions and approximations. For example, a uniform radiance sky is often used to model the diffuse sky radiation. This and other approximations need to be tested against validation data. More significant perhaps than these approximations is the *mode* of the evaluation for all of the techniques referenced above - they all calculate irradiance *at a point*. This mode of evaluation, referred to here as point-based, places considerable limitations on the scope of any analysis that can be undertaken using the technique. For example, the point-based methods do not offer any means of visualising the inhomogeneous distribution of irradiance.

Additionally, they are not suited to automated surveys of available irradiance across cities. These and other limitations are discussed in greater detail in a later section.

New approach

An entirely new approach was formulated to overcome the limitations of the point-based methods. The design goals for the new approach were as follows:

- The accurate prediction of the incident irradiance on building facades based on hourly (or sub-hourly) basic data, e.g. Test Reference Year (TRY).
- There should be no practical limits placed on the scene complexity.
- Shading of and inter-reflection between buildings must be accounted for.
- Realistic sky radiance patterns to model non-overcast sky conditions must be included.
- Results should be presented as irradiance images.
- Automation of the process must be possible.

These aims were realised in a new simulation approach that uses physically-based rendering and data visualisation techniques. The new approach is called Irradiance mapping for Complex Urban Environments or ICUE (pronounced IQ). The theoretical basis for the new approach and demonstration examples are described below.

ICUE

Theoretical bases for the new approach

Theoretical Basis I

For annual totals of irradiance founded on hourly (or sub hourly) basic quantities, irradiance renderings for all of the 4,000 (or more) actually occurring sun positions can be effectively synthesised from a much smaller number of renderings by transforming the problem from the time-series domain to the sun-position domain.

This transformation involves several stages. First, the above-horizon sun positions that occur annually at the locale (e.g. city) are computed using standard equations [8]. Although a timestep of 1 hour is usual for TRYs, a 15 minute time-step for the year is used as the default to ensure a smooth distribution. The sun positions for Leicester, UK are shown in Figure 1(a). The distribution in altitude and azimuth is then divided into 'bins' using a grid of arbitrary resolution, Figure 1(b). Here a grid size of 8˚ was used for both angles. The number of sun positions that occurred in each bin are counted, and the bin-mean sun position evaluated, Figure 1(c). The number counted for each bin is indicated by shade (see adjacent legend), and the bin-mean position is marked by a cross (**x**). For this combination of locale (i.e. occurring sun positions) and bin size, there were 179 bins that contained one or more sun positions. A series of 179 irradiance renderings are then computed - one each with a normalised radiance sun at the bin-mean sun position. The annual-total irradiance image due to the sun is synthesised from these 179 irradiance renderings (see Theoretical Basis II below).

The total number of above-horizon sun positions was - at a 15 minute timestep - 17,635. That is, about 4,400 at a timestep of 1 hour. A similar procedure is carried out to determine the sun positions for the anisotropic (that is, non-overcast) sky contribution. The circumsolar component of diffuse radiation from the anisotropic sky is less directional than that from the sun. Thus a larger binsize (i.e. 16˚) is used which gives just 52 sun positions, Figure 1(d).

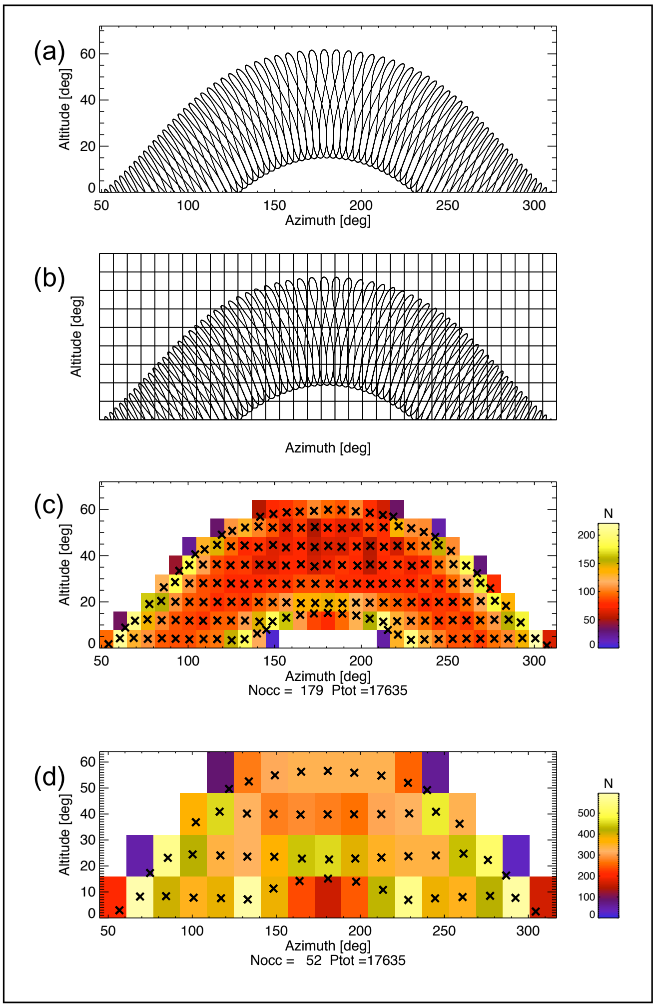

Figure 1. Procedure to determine the sun position for the sun and the anisotropic sky renderings from the distribution of annually occurring sun positions (15 minute timestep)

Theoretical Basis II

For any fixed (*or almost fixed*) configuration of self-radiant entities (i.e. sun or sky) in a scene, an irradiance image of the scene is equal (*or almost equal*) to the normalised irradiance image multiplied by the magnitude of the radiant output of the source configuration.

Theoretical Basis III

The irradiance *effect* of a sky model blend can be synthesised from irradiance images created using 'pure' sky model types. In other words, the irradiance image that would result from some composite sky radiance distribution, say that for a mixture of an overcast sky an intermediate sky, can be synthesised from the irradiance images for the separate sky models. An example two-component sky model blend is shown in Figure 2. Here, an intermediate and an overcast sky were blended to produce a 'half-and-half' composite sky.

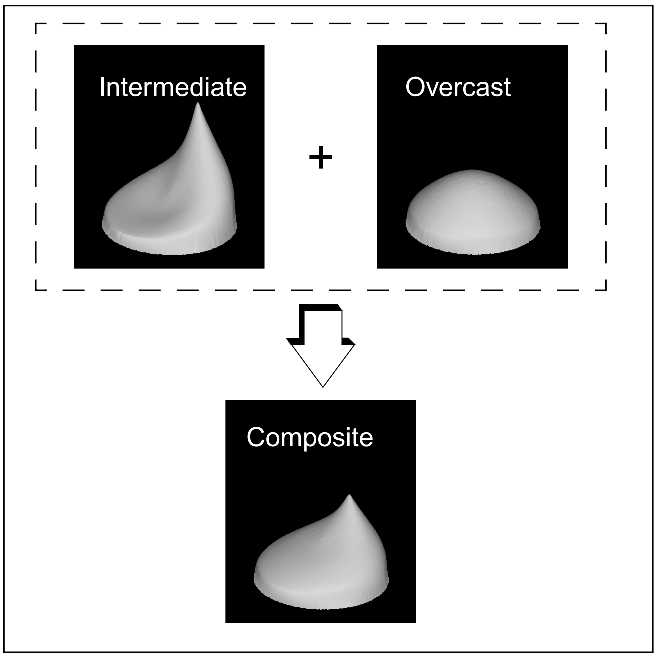

Figure 2. Synthesis of a composite sky model.

Implementation

The ICUE Simulation System

The ICUE approach is currently implemented in software on a UNIX workstation as an 'expert-user' tool for proof-of-concept, demonstration and research. The ICUE simulation system is a suite of programs and scripts to initiate, process and view irradiance images. The irradiance images are created using the freely-available (UNIX) *Radiance* lighting simulation system [9].

The ICUE process has been optimised at various stages, most significant of which is the transformation of the problem domain (see Theoretical Basis I above). Nevertheless, the computational requirements are significant. The creation of the irradiance images (that is, the renderings) is the most time-consuming stage of the process, usually carried out as an overnight 'batch job'. Thereafter, the operations are largely interactive.

Precise computational demands, such as processing time and memory requirements, depend on several factors and are difficult to anticipate. There is a complex relation between rendering time, the rendering parameters and the scene complexity. Suffice to say that, the ICUE system has been successfully applied to very complex city models (see below) using less than the state-of-the-art in (single-processor) computer hardware.[1]

The ICUE system is, at the time of writing, functional for practical use and research purposes, but in need of further development to refine some of the operational modalities (these are described in a later section). Although it is not practical at this stage to make the ICUE simulation system itself available to 'end-users', output from ICUE can be linked to 'end-user' GIS systems. An example of this is described in a later section. The authors are investigating the possibility of an 'end-user' version of ICUE, though this is not an immediate prospect.

Computation

For any given location, the bin-mean sun positions for the sun and the sky renderings are determined from the distribution of actually occurring sun positions. Then, for any given view, normalised irradiance renderings are created for the sun (179 renderings), the anisotropic sky (52 renderings) and the CIE overcast sky (1 rendering). These numbers are for Leicester using the bin-sizes in Figure 1. The rendering process can be distributed across multiple workstations/processors if available.

When the rendering process is complete, the annual-total irradiance images are synthesised from the normalised irradiance images and the basic quantities of a TRY for the locale. A sky model mixing factor is derived for each timestep of the TRY. Based on sky clearness index, this factor determines the relative proportions of anisotropic and overcast sky used to model the diffuse sky contribution at each timestep. Note that a sky model blend containing any number of anisotropic sky types could be used, and at varying bin sizes, though this would add to the overall number of normalised renderings.

Irradiance image totals for the sun and the anisotropic sky are evaluated separately by cycling through all the bins in each respective bin distribution, and summing the contribution for all the sun positions in each bin. The annual-total irradiance image for the overcast sky is computed in a single step. Monthly totals can also be synthesised using a similar method.

Example application

A prototype ICUE system was used to create annual-total irradiance images for a relatively simple model of the De Montfort University Leicester Campus (see later section) and part of the San Francisco city model. The San Francisco model is one of the most complex ever created. It was chosen to prove that ICUE is highly scaleable: the system does not contain any practical limitations on scene complexity.

Normalised renderings for several views of the San Francisco model were created using the method described above. San Francisco is at a lower latitude than Leicester. So, using the same bin-sizes as the example given in Figure 1, normalised irradiance renderings for 207 sun and 58 anisotropic skies were needed. Annual-total irradiance images were then synthesised from the renderings using hourly TRY data for San Francisco. An image for one of the views is shown below, Figure 3. For this scene, higher annual-total irradiances were predicted for (un-shaded) West-facing facades than for East-facing. This is a consequence of the San Francisco weather: the morning fog attenuates the direct sun irradiances (this can be seen in the TRY).

Fine-tuning and Validation

The ICUE system was designed to use arbitrary bin-sizes for the computation of the sun and the anisotropic sky irradiance. As noted, direct radiation from the sun is more directional

1. The latest multi-processor workstations would have done the same job in about 10% of the time.

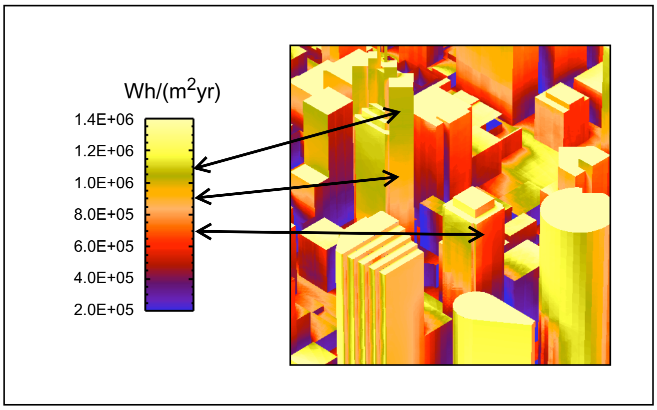

Figure 3. Annual-total irradiance map for San Francisco (based on VRML model).

than diffuse radiation from an anisotropic sky. The bin-size used for the sun component was 8°. This bin-size is *commensurate* with a timestep of approximately half an hour (because the sun traverses an arc of 15° every hour). Thus, the 179 bin-mean sun positions are sufficient to model the hourly variation in sun position at the hour timestep of the TRY. Similarly, it was proposed that the 52 bin-mean (sun) positions were adequate to model the less-directional diffuse radiation from the anisotropic sky. Note that, whatever the positional resolution of the ICUE calculation (that is, bin-sizes), the temporal resolution is always as good as that of the TRY. There remains some 'fine-tuning' work to be done to optimize the balance between computational efficiency (large bin-size) and positional accuracy (small bin-size).

Allied to the 'fine-tuning' is the issue of validation. The first author has carried out rigorous validation work on the *Radiance* system [10,11]. A comparison with those proven lighting simulation techniques indicates that ICUE is a potentially very accurate system. Further evaluation using an actual city-based validation dataset is desirable.

ICUE MODALITIES

The ICUE system was designed to be used in several different ways (called here modalities) depending on the nature of the analysis.

Target mode

This mode is used to compute an annual-total irradiance image for one or more arbitrarily selected viewpoints. The 3D model used could be a few simple shapes for, say, a house with nearby obstructions, or a highly-detailed and extensive city model. Or anything in-between. The user would select view parameters that reveal, to best effect, the facades for which solar installations, e.g. PV, are under consideration and for which a reliable prediction of available irradiance is needed.

Survey mode

The ICUE approach is ideally suited to the automated creation of renderings for the purpose of surveying, at any scale, the incident irradiance on any number of buildings. In this mode, the target area is 'inched' across a city model in, typically, a grid pattern, Figure 4. The user specifies a grid dimension appropriate to the complexity and the scale of the buildings. For example, a different grid for areas of high-rise buildings from that for low-rise urban sprawl and residential housing. In the solar energy planning (SEP) system (described below), the results from an ICUE survey mode analysis are linked to a GIS database.

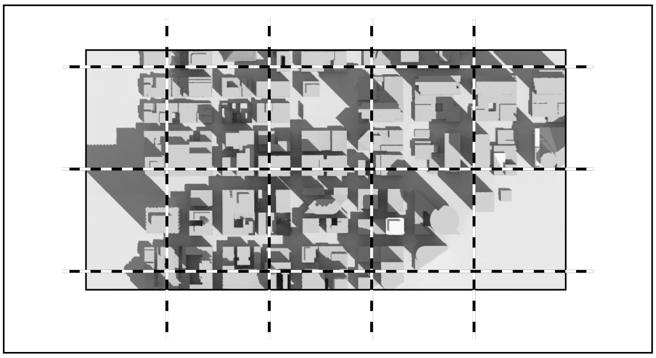

Figure 4. User specified grid for automated irradiance mapping of city model (San Francisco).

Impact assessment

Any new building or structure (e.g. vegetation) will add to the shading experienced by existing nearby buildings. Where PV or solar heating systems are already installed, their efficiency will be reduced by the introduction of additional shading. ICUE could be used to accurately quantify the reduction in available irradiance caused by a new obstruction. Furthermore, the reduction in irradiance can be visualised using a technique referred to here as 'difference mapping'. For this, two renderings of annual-total irradiance are created using the same view parameters - one for the existing scene and the other with the new building or structure in place. An image of the reduction in total annual irradiance is simply the difference between the two. Once again, the reduction in total annual irradiance can be read from the difference image using the cursor.

Because the predictions are based on TRY data for the locale, a reliable measure of the degradation in performance of a solar installation can be made. This degradation could be converted into a measure of 'financial injury' as a basis perhaps for seeking compensation from the 'injurer'. Thus the ICUE approach can be used to *quantify* injury in disputes where solar access is deemed to have been infringed.

Time-series mode

Thus far, the prediction of annual-total irradiance has been discussed or demonstrated. The ICUE approach is equally suited to the synthesis of irradiance images for shorter periods, e.g. monthly. Additionally, an irradiance time-series at the time-step of the TRY can be synthesised using, in effect, a reverse of the procedure described in Figure 1. However, it is more practicable to do this for one or more user-selected points in the scene (that is, pixels of an irradiance image) than for the entire image (which would result in the creation of ~4000 irradiance images).

Research

By virtue of its potential accuracy and considerable flexibility, ICUE could be used to investigate the relationship between building form and the irradiance micro-climate [12]. In this respect, ICUE predictions could serve as a 'benchmark' to validate simpler approaches. Additionally, ICUE provides an ideal framework to investigate sky models (and related issues) for the purpose of irradiance prediction in complex environments.

AN 'END-USER' APPLICATION OF ICUE

The Solar Energy Planning System

The results of an ICUE analysis (Survey Mode) have been linked to a GIS-based 'end-user' application called the Solar Energy Planning (SEP) System [13]. An outline of the SEP system and the link with ICUE follows.

SEP Outline

The project aims to develop a methodology that will integrate existing energy-related models and new approaches in a structured way. SEP will offer an instantiation of this methodology as a suite of software tools within an intelligent decision support framework linked to a geographical information system (GIS). The broad approach entails the use of several different applications and programming languages in order to achieve the desiderata of flexibility and transparency in the use of data, intelligent support for the deployment of system components and spatial visualisation of results.

Several components are under development in addition to the link with the output from ICUE (Survey Mode). These address the issues of domestic solar water heating and passive solar design of new developments as well as the photovoltaic energy potential of commercial and public buildings. Each aspect carries a different set of problems requiring distinct approaches to data-capture, modelling and visualisation. These must be solved within the overall constraints, such as cost, motivation and available expertise, dictated by the projected end-use. To ensure this, the system is being developed and prototyped iteratively in close contact with sample end-users in order to ensure that most issues of usability and conformance to requirements are resolved before delivery. This approach, together with the realistic and multi-levelled conceptualisation of the problem and its solution, should help to secure the goal of a system that will be instrumental in shaping policy towards greater and more coherent utilisation of solar energy.

Linking ICUE Irradiance Maps to SEP

For the irradiance mapping component, a 3D model is needed. To date, most 3D models have been developed independently of any GIS system. Furthermore, the physically-based rendering used in ICUE produces a view-dependant irradiance map. It makes no sense therefore to attempt to map the irradiance values in the renderings *back* to the 3D model. Even if that were possible, there remains the problem of integrating 3D models with GIS and data visualisation - these are areas of considerable research activity and, at this point in time, many of the issues remain unresolved [14].

These problems notwithstanding, a *connection* between the irradiance images and the GIS was devised which gave geographical context to the irradiance mapping. It is intended for irradiance images created using the Survey Mode of the ICUE system. The grid for the irradiance images of the city-model (Figure 4) is mapped to the GIS co-ordinates (i.e. geo-referenced). For each grid-section of the city model, irradiance images are computed for five standard viewpoints: zenith and the four mid-compass directions. For the zenith view, each irradiance image can be accurately super-positioned over the GIS map as a 'tile' because the grid has been geo-referenced, Figure 5. To the user of the SEP GIS, the irradiance image indicates that this section has been surveyed using ICUE and that irradiance images (that is, data) for this and other views are available. A 'click' inside the image tile launches the Viewing Tool (Figure 5). The user can then examine any of the views and rapidly establish the incident irradiance on of the visible building facades. This connection between the GIS and the irradiance mapping is referred to as a 'soft-link'. It offers a practical solution given the constraints of the various modelling approaches involved. Furthermore, it offers an effective GIS context for a city-wide survey of available irradiance.

The ICUE system is presently UNIX-based and requires expert configuration. With the 'soft-link' approach however, the results of ICUE used in Survey Mode can be made available to 'end-users' of planning tools.

COMPARISON WITH EXISTING TECHNIQUES

ICUE versus 'point-based' calculations

A rendering-based approach is far more comprehensive than a points-based calculation - the irradiance is calculated at every pixel in the field of view rather than for just a few points. The inhomogeneous distribution of irradiance in complex environments is easily appreciated from the irradiance renderings. It is of course possible to repeat a points-based calculation many times over and from the results attempt to construct a 'picture' of the inhomogeneous distribution of irradiance in an urban environment. However, multiple points-based calculations share various shortcomings.

Firstly, for simulation-based methods (e.g. [5] and [7]), there is the problem of specifying the coordinates for the calculation points. For building facades that are not parallel to one of the axes, the placement of the calculation points and the evaluation of surface normal must be computed separately. For manual projection-based methods (e.g. [6]), the projection of the obstructions must be evaluated for each of the calculation points. Secondly, and this applies to all of the points-based methods, they do not posses an effective mechanism to relate the irradiance predictions to the scene geometry. Thus the user would have to employ a considerable amount of imagination to 'visualise' the inhomogeneous distribution of irradiance based on a number of predictions for various points. Lastly, none of the points-based methods are suited to automated surveys of available irradiance.

With the ICUE approach, none of the above limitations apply. Calculation points, surface normals etc. are defined automatically by the view parameters which can be either user-defined or based on some automated scheme. For display and analysis, the irradiance image is false-coloured and viewed directly. Additionally, the irradiance at each pixel can be read using the cursor. By automating the generation of the view parameters, it is possible to automate the simulation process entirely. Thus a ‘mosaic’ of irradiance images for an entire urban area can be generated with minimal user effort (i.e. Survey mode).

CONCLUSION

A new approach to predicting irradiance in complex urban environments has been described. The examples given in this paper have demonstrated that the new approach offers a significant advance over existing methods. In comparison with points-based methods, the ICUE system is image-based, scaleable and automated. This more than justifies, in our opinion, the computational requirements. A prototype of the link between the ICUE system and a solar energy planning tool has been presented.

Note

These images in this paper are best appreciated using colour. A set of colour figures are available on-line at:

http://www.iesd.dmu.ac.uk/~jm/plea2000

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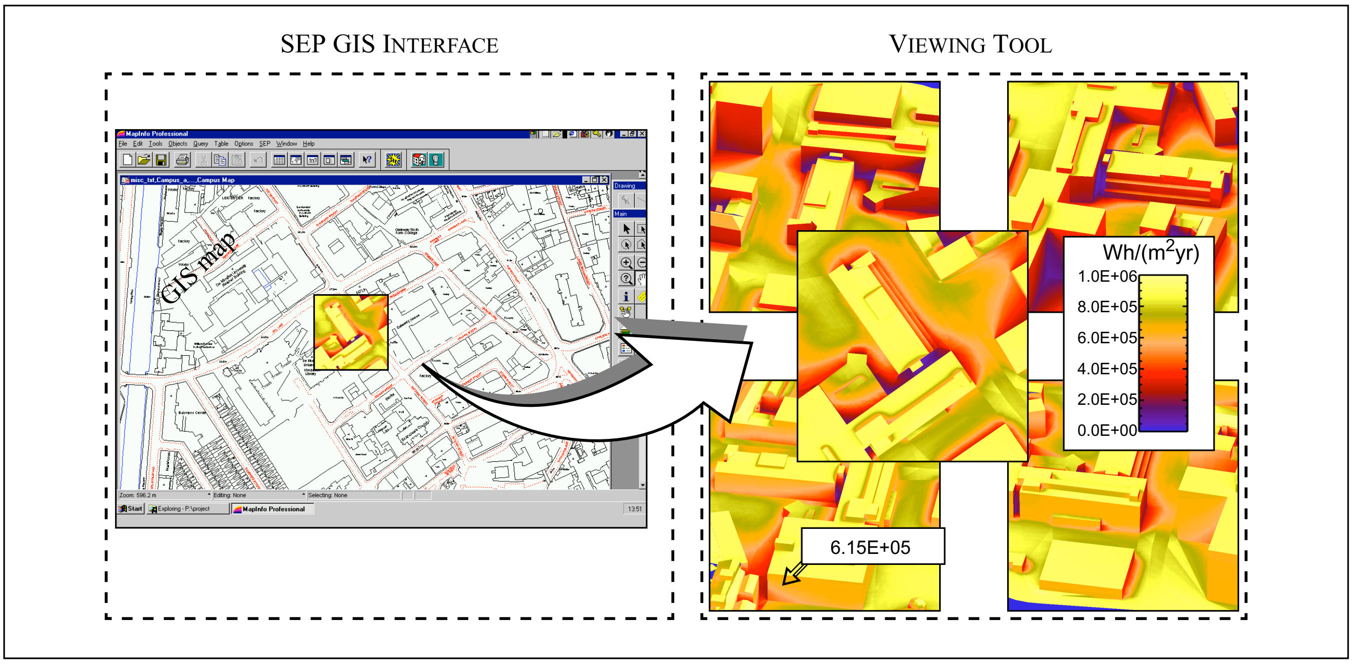

Figure 5. Illustration of ‘soft-link’ between the Viewing Tool and SEP GIS. A ‘click’ in the GIS window launches the Viewing Tool. Inset on irradiance image (bottom-left) demonstrates cursor reading of pixel irradiance value.