THE EKIHOUSE: AN ENERGY SELF-SUFFICIENT HOUSE BASED ON PASSIVE DESIGN STRATEGIES

O. Irulegi*, L. Torres, A. Serra, I. Mendizabal, R. Hernández

Quality of Life in Architecture and Urbanism Group, University of the Basque Country, Department of Architecture, Plaza Oñate 2, 20018 San Sebastian, Spain

Abstract

The EKIHOUSE is an industrialized solar house prototype, designed and developed by the University of the Basque Country for the SOLAR DECATHLON EUROPE 2012 competition held in Madrid (Spain). The building design strategies are based on the full integration of active - passive solar technologies and passive design criteria in order to achieve an energy self-sufficient proposal, providing high quality of life to its occupants. Despite its intentionally small surface area (54.6m^2), the house can be adapted to suit a wide range of lifestyles thanks to its flexible, multifunctional open plan design that can be visually and physically expanded outdoors by removing the northern and southern glazed façades (PVC joinery and 0.9kW/hm^2 ºC glass). For ease of transport and assembly, the EKIHOUSE consists of a modular CLT structure system (two 12.60m x 3m modules) that supports the photovoltaic roof (10kWp) which functions as a canopy to protect the southern facade from direct solar radiation thereby reducing overheating problems in the building interior. In order to control the indoor temperature , PCM panels are mounted in the ceiling. When passive strategies are insufficient in extreme conditions, the house is also equipped with a ventilation and air-conditioning system that allows a 90% energy recovery. Furthermore, an outdoor evaporative cooling system helps lower the ambient temperature by up to 4 °C. A rain and greywater treatment and purification system is also installed. The operation of all this active technology is controlled by an optical domotics system.

Keywords: industrialized construction, CLT modular structure, full integration of active and solar systems, bioclimatic design, optical domotics control.

* Corresponding author. Tel.: +34 943017115; fax+34 943 01 51 70.

E-mail address: o.irulegi@ehu.es (O. Irulegi).

Highlights:

-Full integration of active - passive solar technologies and passive design criteria to achieve an energy self-sufficient house.

-Project strengths: the energy production potential, adaptability, flexibility, capacity of passive strategies to respond to external conditions in order to offer hygrothermal comfort and energy self-sufficiency.

-The Ekihouse has five active systems to maintain the interior comfort level: a Photovoltaic system, HVAC system, Evaporative Cooling system, Plumbing system and Building Control system.

-Industrializable and timber-based modular construction.

1. Introduction

The Ekihouse[†] is a solar house prototype designed and developed by the University of the Basque Country for the Solar Decathlon Competition [1]. The main feature of this building is the full integration of solar technology [2], passive[3] and active design criteria to achieve an energy self-sufficient proposal [4], providing high quality of life standards to its occupants [5]. Therefore, the mayor challenge of the Ekihouse is to convert the potential opportunities of renewable energies sources and state-of-the-art technologies into a functional architectural solution, creating comfort and psycho-emotional well-being through the choice of harmonious proportions, use of natural light and the selection of natural materials [6][7].

The house is rectangular in shape (12.60m x 6m, useful area: 54.6m^2) standing on a square platform (15m x 15m) where the main façade faces south. The building is wrapped in a continuous metal skin ,recreating a Basque forest scene (Fig. 1). Depending on the specific orientation, the skin has different properties in order to improve the passive thermal performance of the house.

The Ekihouse is designed to be open plan, offering the possibility of catering for a wide range of lifestyles due to its flexible multifunctional area that can be expanded outdoors (Fig.2). The spatial and ambient

[†] "Eki" comes from the Basque language (euskera) and means "sun".

versatility is enhanced by the solution adopted for the two main façades, one south facing and the other north facing. Both feature sliding glass walls, with removable shading and exterior layer elements that allow different configurations (Fig.3). According to this, the platform where the house stands is not only an exterior space but an extension of the interior space (living room, studio, bedroom, bathroom, etc.) when the façade elements are fully removed. The façade is not a compromise solution for the whole year, moreover, it offers opportunities to adapt to each individual user, rather than being a best average for all, as is usually recommended in the different standards [8][9].The building is adaptable to seasonal climate trends so that the house can become a compact self-contained space for minimal winter energy loses whilst expanding in summer to allow cross ventilation and outdoor activities in keeping with the Mediterranean way of life.

2. Design description and process

2.1. Bioclimatic approach

Considering the specific location and seasonal climate variability in Madrid, a preliminary climate assessment was carried out in order to evaluate the effectiveness of a number of bioclimatic strategies establishing the potential impact on the overall energy performance and comfort conditions [10].

According to the Köppen-Geiger climate classification, Madrid has a dry, typical steppe climate (BSk, observed period:1976-2000) [11]. In summer, the temperature ranges from 15ºC to 32ºC. However, in winter the temperature range is significantly lower, from 2ºC to 12ºC (Fig.4).

In compliance with the ASHRAE Standard 55-2004 PMV (Predicted Mean Vote) comfort model, a bioclimatic chart was obtained and the most effective passive strategies established. These main strategies are: shading and cross ventilation for summer solar exposure and the use of internal gains for winter [12][13][14].

2.1.1. Summer period strategies:

In June, July, August and September, the average temperature in Madrid lies within the comfort range however it is important to highlight the fact that there is a very significant difference between daytime and night-time temperatures. In July, for example, it is normal to record a minimum of 18°C and a maximum of 32°C. For this reason it is important to optimise the design of shading elements to guarantee shade during the hottest hours around midday (Fig.5). Furthermore, it is recommendable that the building is provided with high thermal mass [‡]to reduce the thermal lag and natural ventilation for maximum comfort[15][16]. Finally, considering the temperature decrease at night, internal gains play a significant role.

Based on these objectives, the building can be expanded outdoors and incorporates a canopy to protect the southern facade from direct solar radiation and to reduce overheating problems inside the building. The roof, on which PV panels are mounted, is also ventilated for improved performance and reduced heat transfer inside the building. The energy benefits of using fixed shading devices with integrated PV has been demonstrated [17]. In addition, the southern façade features a removable outer skin made of perforated metal panels in order to control diffuse radiation if necessary. The panel perforations are carefully designed, taking into account visual comfort and incident solar radiation in summer.
By removing the southern and northern façade elements, the excessively daily accumulated heat can be quickly dissipated at night-time thanks to what is known as the cross ventilation strategy. In order to flatten out the thermal lag and balance temperature peaks inside the house, PCM is mounted in the ceiling, the benefits of which have been widely investigated [18].

2.1.2. -Winter period strategies

In January, February , March, November and December comfort is not usually achieved in Madrid either by day or at night (Fig.6). For this reason, it is recommendable for the building design to consider solar exposure, good orientation and an optimal window design and size. A heating system would be necessary whenever temperatures of 0°C are recorded outdoors.

According to these specific objectives, the building is self contained in winter, the outer skin of the southern façade can be fully removed to maximise solar exposure through the glazed surface. On the other hand, thanks to the highly insulated outer skin of the northern façade, energy losses can be

[‡] Thermal mass as a bioclimatic strategy has not been achieved because of the payload limitations for the competition prototype but its implementation is foreseen in future versions.

minimised. In addition, the ceiling mounted PCM helps to flatten out the temperature peaks by dissipating the daily accumulated heat at night (Fig.7) [19].

2.2. Ekihouse energy design optimization

The energy performance analysis and the definition of the architectural design concept of the Ekihouse were developed simultaneously, integrating the bioclimatic requirements in order to evaluate their mutual interactions. To achieve this goal, we primarily used the *Energy Plus* simulation software by the *DesignBuilder* graphical user interface (GUI).

To achieve these objectives, 5 models were developed:

- "Initial basic" model,
- "Thermal envelope" improved model,
- "Sun shading envelope" improved model,
- "Facade" improved model,
- "Natural ventilation" improved model.

2.2.1 -Model 1: The basic model

The initial model was the starting point for the construction of both the architectural and the energy performance concepts.

2.2.2 -Model 2: The thermal envelope improved model

The thickness of the insulation and the thermal features of the openings were modified.

2.2.3 -Model 3: The sun shading envelope improved model

Solar protections over the southern and northern windows were needed. In order to ensure the complete shading of the house openings, a 2 meters long projecting element on the top of southern facade was designed, and a one meter long projection on the northern facade. In order to minimize the direct solar radiation and indirect diffuse radiation gains coming from the reflected light from the ground, a 50% -perforated steel sheet to reflect 50% of the radiation was mounted over the entire envelope.

2.2.4 -Model 4: Facade improved model

Some movable elements were designed to help get different façade configurations for maximum energy efficiency.

- The sliding glass allows the facades to be easily opened for different natural ventilation strategies.

- The perforated sheets on the southern facade are removable for improved solar gains.

- The perforated sheets with cellular polycarbonate on the northern facade allow the light to be controlled in the building interior and, by adding thermal resistance, they reduce heat losses in winter.

2.2.5 -Model 5: The natural ventilation improved model

A CFD analysis was used to calculate the ventilation flow obtained by natural convection generated by opening the windows with a specific and optimized schedule obtained by analysing both a typical summer week and a winter week.
At every step many different energy parameter were calculated in order to understand and evaluate how to improve the overall Ekihouse performance. The competition rules required yearly heating and cooling simulations, so these were the primary parameters checked by the analysis. The next figures show the main results of the simulations (Fig.8 and fig.9).

The ventilation rates of the last three improved models are shown in Table 1 below.

3. Construction and structural description

As the Ekihouse is an industrializable prototype, those concepts related to ease of transport and assembly are taken into account right from the early design stages. The Ekihouse consists of a modular CLT structure system which can be easily transported in standard trucks (two 12.60m x 3m modules) (Fig.10). The CLT system is reinforced with 60 x 24cm laminated timber beams that permit a light span of 10 meters in the Northern and Southern façades where the roof projects 1m and 2m respectively. Thanks to this distance, the façade components can be completely removed and concealed in the lateral ventilated boxes.

The PV roof operates as a canopy to protect the southern facade from direct solar radiation and to reduce overheating problems inside the building. The PV panels are mounted on a laminated steel substructure that rests directly on the structural modules (Fig.11).

4. Use of Active Systems in the Ekihouse

The Ekihouse has five active systems to maintain the interior comfort level: Photovoltaic system, HVAC system, Evaporative Cooling system [20] Plumbing system and Building Automation system (Fig.12).

4.1. Photovoltaic system (Atersa S.L.)

The photovoltaic system is specifically designed to provide electric energy to the Ekihouse bearing in mind that the architectural specific requirements and calculations are based on the irradiance and temperature conditions of Madrid. In general, the photovoltaic system comprises two independent production units (2 x 50 kWp). Each unit is equipped with an inverter (50 kWp) and 28 panels arranged in two strings. This individual configuration provides a maximum power point tracker for each string. The Atersa A-214P PV panels have 60 series mounted polycrystalline tempered glass solar cells. Under standard test conditions of 1 kW/m2 of solar irradiance and 25ºC cell temperature; they typically give a maximum power of 214 Wp. For optimal PV panel performance, an evaporative cooling system will be installed.

4.2. HVAC system (Alder Venticontrol S.A.)

The house makes the most of the outdoor climate conditions to offer an orientation-dependent response. The northern and southern facades of the house are fully configurable, allowing solar radiation in winter and cross ventilation in summer. When passive solutions are insufficient to achieve comfort, then HVAC systems come into operation. There are two accumulators, one for the solar panels and another for the heat pump where the hot water produced is stored for later use if required. A hot water return system helps save energy. In summer, when the outdoor temperature is lower than the indoor temperature, comfort is achievable by a ventilation system. In addition, there is an air and dehumidification cooling system. These systems work as a heat exchanger. The hot and cold air will be distributed through a five-duct heating module: three ducts will be responsible for boosting air into the house whilst the other two will be responsible for removing it.

4.3. Evaporative cooling system (Frialia Microclimas S.L.)

All cooling systems are based on a natural process that uses water as a coolant. This system works by the evaporation of water: in this process the water passes from liquid to vapour, consuming energy and capturing heat from the air, lowering the temperature and increasing the humidity. Evaporative cooling is a process that has been present in our daily lives since times of old. The jug, the jar, the fountains, the sea breeze and even the phenomenon of sweating, are all examples of evaporative cooling. Frialia Microclimas allows a 75%saving in the pump power supply and can operate with treated water. The nozzles have 0.7 mm orifices to produce water droplets of 12 microns, which facilitates evaporation and increases performance.

4.4. Plumbing system (Roth-Global Plactic S.A.)

The hydraulic system installed at the Ekihouse is designed to reduce energy consumption and maximize water savings in the context of the architectural design of the house. This is achieved by differentiating between the various water potability and recyclability levels, with. three supply ducts to provide drinking water, rainwater and treated grey water. However, there are two effluent lines , differentiating betweensewage and greywater. Greater savings can be made in water reuse if proper water treatment provided. The Ekihouse features a new system for recycling greywater: the Aquaserve, designed to reuse domestic greywater from showers and baths for toilet flushing, watering gardens, washing cars, etc.

4.5. Building automation system (Schneider-Electric S.A.)

The Ekihouse has an automated management system for its basic functions, for greater occupant comfort and convenience. The system makes it possible to achieve a practical gain in terms of comfort through intuitive and easy handling with no over-complicated procedures. The user has constant control of the building at all times. The automation provides maximum control over all equipment, resulting in high efficiency and comfort for the Ekihouse occupants. Therefore, all appliances will be compatible with the intelligent management system based on the KNX (Konnex) protocol. Thanks to this, the lighting, air conditioning and electrical circuit consumption are controlled and monitored. The lighting system has a DALI gateway with a wireless pushbutton instead of wired pushbuttons. Switch-timers are installed in the circuits powering each item of equipment, so that each one has a specific operating time to avoid energy consumption overlapping and peaks. The house system management is based on an Android tablet for simplicity, convenience and efficiency. Furthermore, this system has also an internet router for the remote management of the house systems..

5. Photovoltaic System

The main purpose of the PV system is to provide energy for the everyday house operation and to offset the energy consumption of its inhabitants during their work, thereby helping to reduce the dependence on non-renewable energy sources (Fig.13). Thus, the energy produced by the Ekihouse accompanies the householders through the power network and even if transmission losses may limit the range of this approach, it’s possible to assume that for a heterogeneous urban tissue the energy produced by the system can be consumed locally.

The PV installation of the Ekihouse is a grid-connected system with a theoretical power peak of 11.98 kW, comprising 2 inverters and 56 solar panels arranged in 4 strings of 14 modules each. The individual PV modules comprise 60 series-mounted 156x156 mm polycrystalline silicon cells, with a module efficiency of n=13,14%.

PV System Performance

As is well known the performance of a PV system depends on many different variables such as irradiance, temperature and wind speed. Due to the stochastic nature of these variables it’s difficult to assess the accuracy of a forecast. As is shown in Figure 14 the short-term variation of these variables has a significant impact on the daily energy production values if compared to our initial estimates based on the weather conditions over the last ten years for Madrid. However, if the cumulative energy production is obtained, even for this short period of time, it shows that these daily differences are offset, meeting the long term trend represented by the 10 year based estimate.

Furthermore, the specific values of irradiance, wind speed and temperature recorded during the competition period allowed us to obtain a second estimate that has been then compared with the empirical production data in order to assess the accuracy of the model built for this particular purpose (Table 3).

Subsequently, the differences between this second estimate and the empirical data were calculated (Table 4) showing a slight persistent negative bias. Additionally, since there appears to be a weak relationship between the calculated error and the wind speed (Fig.16), this suggests that the previously disregarded lower surface of the PV modules , may partially contribute as a convective surface over a certain wind speed threshold , lowering the cell temperature and allowing an increase in power generation.

5.1. -Energy Balance and Carbon Footprint

The results obtained during the contest period show a net surplus amounting to 239 kWh of energy. In a year round scenario this could represent a net energy generation of 8313 kWh/year. Therefore, considering an average level of CO2 emissions for the Spanish grid of 0.34 kgCO2/kWh, the net energy produced by the Ekihouse may represent a mitigation of 2800 kgCO2/year (Table 5) (Table 6).

6. Transport and assembly

The transport of the house is an important point to be considered in industrialized modular construction, for this reason from the beginning of the project the house was designed to be built by assembling two main modules. Thanks to this early decision, both modules can be easily transported using standard trucks, thereby facilitating the entire process is facilitated and reducing the environmental and financial costs (Figure 17).

The Ekihouse was delivered to the Villa Solar in four vehicles:

- Two special trailers (16.5 x 3.45 x 4.5 m): Transport of the house in two modules.

- Two standard-size truck (16.5 x 2.5 x 4 m): Transport of the photovoltaic system, joinery and security equipment, construction equipment, foundations, deck structure and deck wood.

The construction comprises 11 stages (10 days):

Stage 01: Arrival of construction and security elements, and setting up work areas (1 day).

Stage 02: Setting up the crane to the south-west area (1/2 day).

Stage 03: Beginning of construction and foundation validation by an inspector (1/2 day).

Stage 04: Delivery of the two main house modules (1/2 day).

Stage 05: Assembly of the modules (1/2 day).

Stage 06: Delivery of the photovoltaic system (1/2 day).

Stage 07: Mounting of the solar panels on the roof (2 days).

Stage 08: Arrival of the joinery (1/2 day).

Stage 09: Construction of the deck foundation (1 day).

Stage 10: Deck construction and finishing house interiors (2 days).

Stage 11: Ground clearance (1 day).

7. Market viability

The Ekihouse is a competitive, industrialized house that has many advantages to be competent and attractive in the current market, promoting sustainable construction. As the Ekihouse consists of two longitudinal modules, it offers flexibility in adapting to meet the requirements of the user's family, by either increasing or decreasing the surface area (Fig.18). Moreover, as many component parts are prefabricated, the house has a cost-effective production and short delivery times. Assembly is by dry mounting and, since the modules operate individually, once at the construction site, the two parts simply need to be connected together, a process which can be performed in less than two weeks.

The prospective buyer is part of generation x: active, balanced and happy; amounting to 1.131.000 potential buyers in Spain . The Ekihouse offers the following strong points to buyers. esign advantages: practical size, that is adaptable to lifestyle changes (children, workspace, etc); bright and airy; fluent contact with nature; hi-tech. Economical advantages: affordability; low operating cost; net energy producer. Environmental advantages: the use of renewable energies;, high energy efficient systems; greywater re-usage; low urbanization impact. Furthermore, a feasibility study has revealed that the Ekihouse is affordable, with the two modules costing 250.000 euros. Depending on demand, the cost could be significantly reduced (Economies of scale reduce the unit cost by almost 30%.):

-up to 18 units: 234.021 EUR

-up to 42 units: 218.973 EUR

-up to 489 units: 169.155 EUR

8. Competition weeks. Results

During the competition weeks the climate conditions varied significantly. The relative humidity ranged from a minimum of 29% and a maximum of 93% with an average value of 60.7%. On the other hand the temperature ranged from a minimum of 8.9ºC and a maximum of 30.1ºC with an average value of 18.45ºC. Inside the house the relative humidity ranged from a minimum of 24.85% and maximum of 88.15% with an average value of 41.73% whilst the temperature ranged from a minimum of 18.5ºC and a maximum of 30.2ºC with an average value of 24.31ºC (Fig.19).

The interior peak values were recorded when the HVAC systems were not operating and passive strategies were not effective due to the high occupancy of visitors or to the fact that the house was closed at night. In general it should be highlighted that the interior values for temperature and humidity were generally inside the comfort range (Fig. 20).

9. Discussion and conclusions

The Ekihouse is a multidisciplinary Project which has counted on the collaboration of students from: engineering, communications, marketing, design and business. The project was directed at developing and implementing solar energy based technologies for the residential market (Fig. 21). With this objective, many departments and faculties are taking part in the Ekihouse project. Lecturers, researchers, students, etc. are participating in the development of different aspects of the competition; this has been made possible by incorporating the project in the teaching programme, workshops, final projects, or voluntary works. Collaboration with external research centres, enterprises related to construction and energy is another aspect of the work. Thus, Ekihouse integrates enterprises from the wood, solar energy, engineering sectors , etc. and public institutions. In this respect, the competition is an effective platform for the dissemination of the capacities, technology and production of Basque enterprises in Spain and abroad (Fig. 22).

Furthermore, Solar Decathlon is also a public event intended to achieve increased energy use consciousness in the residential field. The competition demonstrates that it is possible to achieve an attractive house that generates sufficient energy for artificial lighting, cooking, electronic devices. The competition shows that the use of renewable and clean energies, such as solar energy, can provide enough energy to live, work and to enjoy healthy places. Because of all these aspects, one of the main objectives of the Ekihouse project is to make society aware of the viability and potentiality of solar energy and a more responsible use of energy in homes. All these aspects will be published by media, congresses, etc. and completed in the exhibition of the prototype in Madrid and in the provincial capitals of the Basque Country.

Finally, it must be highlighted that the particular conditions of the competition have been a hard test for the house. However, the strong points of the project: the energy production potential , the adaptability, the flexibility, the capacity of passive strategies to respond to external conditions, all functioned correctly in order to achieve hygrothermal comfort and energy self-sufficiency.

10. Acknowledgments (Fig. 22)

List of Figures and Tables

Figure 1: Night view of the EKIHOUSE with the façade elements completely shut.

Figure 2: Night view of the EKIHOUSE with the façade elements completely removed. The inner space is expanded outdoors.

Figure 3: The Ekihouse, a multifunctional open-plan house.

Figure 4: Bioclimatic chart of Madrid.

Figure 5: Passive strategies for summer. Shading and evaporative cooling if needed during the day and cross ventilation by removing the northern and southern façades[§] PCM helps to control the interior temperature.

Figure 6: Passive strategies for winter. Solar exposure during the day and use of internal gains at night. PCM helps to control the interior temperature.

Figure 7: PCM ceiling-mounted panels.

Figure 8: Simulation of heating demand [kWh/m^2] for the five models.

Figure 9: Simulation of cooling demand [kWh/m^2] for the five models.

Figure 10: Structural components of the house.

Figure 11: Construction blow up of the house.

Figure 12: Diagram of the active systems in the house

Figure 13: Ekihouse PV Roof

Figure 14: Daily energy production of the photovoltaic system

Figure 15: Cumulative energy production of the photovoltaic system[**]

Figure 16: Error vs Wind speed

Figure 17: Transport and assembly

Figure 18: Grouping options of the Ekihouse

Figure 19: Outdoor/Indoor Humidity in competition week

Figure 20: Outdoor/Indoor Humidity in competition week

Figure 21: Interior view of the Ekihouse

Figure 22: The Ekihouse Team

[**] An exception should be made concerning the data for September 27th and 28th due to the adverse weather conditions

Table 1: Summary of the ventilation systems and patterns in the third, fourth and fifth models

Table 2: Electrical specification for the PV panels.

Table 3: PV Energy production Wh

Table 4: Difference between predicted energy production values and data recorded

Table 5: Energy balance kWh.

Table 6: Energy production/consumption ratio.

11. References

[1] Solar Decathlon Europe 2012. Available from: http://www.solardecathlon.org.

[2] N. Wang, T. Esram, L.A. Martinez, M.T. McCulley, A marketable all-electric solar house: A report of a Solar Decathlon project, Renewable Energy 34 (2009) 2860 – 2871.

[3] E. Rodriguez-Ubinas, L. Ruiz-Valero, S. Vega, J. Neila, Application of Phase Cahnge Material in highly energy-efficient houses, Energy and Buildings 50 (2012) 49-62.

[4] H. Hu, G. Augenbroe, A stochastic model based energy management system for off-gris solar houses. Building and Environment 50 (012) 90 – 103.

[5] B. Risholt, B.time, A.G. Hestnes, Sustainability assessment of nearly zero energy renovation of dwellings based on energy, economy and home quality indicators, energy and Buildings 60 (2013) 217-224.

[6] N. K. Bansal, G. Hauser and G. Minke, *Passive Building Design – A Handbook of Natural Climatic Control*. Elsevier Science B.V., Amsterdam, 1994.

[7] W. J. Batty, H. Hinai and S. D. Probert, Natural-Cooling Techniques for Residential Buildings in Hot Climates, *Applied Energy*, UK, Vol. 39, pp. 301-337, 1991.

[8] R.C.G.M. Loonen, M. Treka, D. Cóstola, J.L.M. Hensen, Climate adaptive building shells: State-of-the-art and future challenges, Renewable and Sustainable energy Reviews, 25 (2013) 483-493.

[9] A. Mwasha, R.G. Williams, J.Iwaro, Modeling the performance of residential builing envelope: the role of sustainable energy performance indicators, Energy and Buildings 43 (2011) 2108-2117.

[10] S. Stevanovic, Optimization of passive solar design strategies: A review, Renewable and Sustainable Energy Reviews 25 (2013) 177-196.

[11] World Maps of Köppen-Geiger Climate Classification. Available from: http://koeppen-geiger.vu-wien.ac.at/.

[12] A. Ferrante, M.T. Cascella, Zero energy balance and zero on-site Co_2 emission housing development in the Mediterranean climate, Energy and buildings 43 (2011) 2002-2010.

[13] M. J.N. Oliveira Panão, M. P. Rebeleo, S.M.L. Camelo, How low should be the energy required by a nearly Zero-Energy Building? The loadgeneration energy balance of Mediterranean housing Energy and Buildings 61 (2013) 161-171.

[14] M. Praznik, V. Butala, M. Z. Senegačnikc, Simplified evaluation method for energy efficiency in single-family houses using key quality parameters, Energy and Buildings 67 (2013) 489-499.

[15] M. kolokotroni, B.C. Webb, S.D. Hayes, Summer cooling with night ventilation for office buildings in moderate climates, Energy and Buildings 27 (1998) 231-237.

[16] E. Oikonomou, M. Davies, A. Mavrogianni, P. Biddulph, P. Wilkinson, M. Kolokotroni, Building and Environment 57 (2012) 223-238.

[17] M. Mandalaki, K.Zervas, T. Tsoutsos, A.Vazakas, Assesment of fixed shading devices with integrated PV for eficient energy use, Solar Energy 86 (2012) 2561-2575.

[18] M. Pomianowski, P. Heiselberg, Y. Zhang, Review of thermal energy storae technologies based on PCM applications in buildings, energy and Buildings 67 (2013) 56-69.

[19] N. Soares, J.J.Costa, A.R. Gaspar, P.Santos, Review of passive PCM latent thermal energy storage systems towards buildings ‘energy efficiency, Energy and buildings 59 (2013) 82-103.

[20] M. Santamouris, D. Kolokotsa, Passive cooling dissipation techniques for buildings and ther structures: The state of the art, energy and Buildigs 57 (2013) 74-94.

Figure 1: Night view of EKIHOUSE with façade elements completely closed.

Figure 2: Night view of EKIHOUSE with façade elements completely removed. Inner space is expanded outdoors.

Figure 3: Ekihouse, a multifunctional open plan.

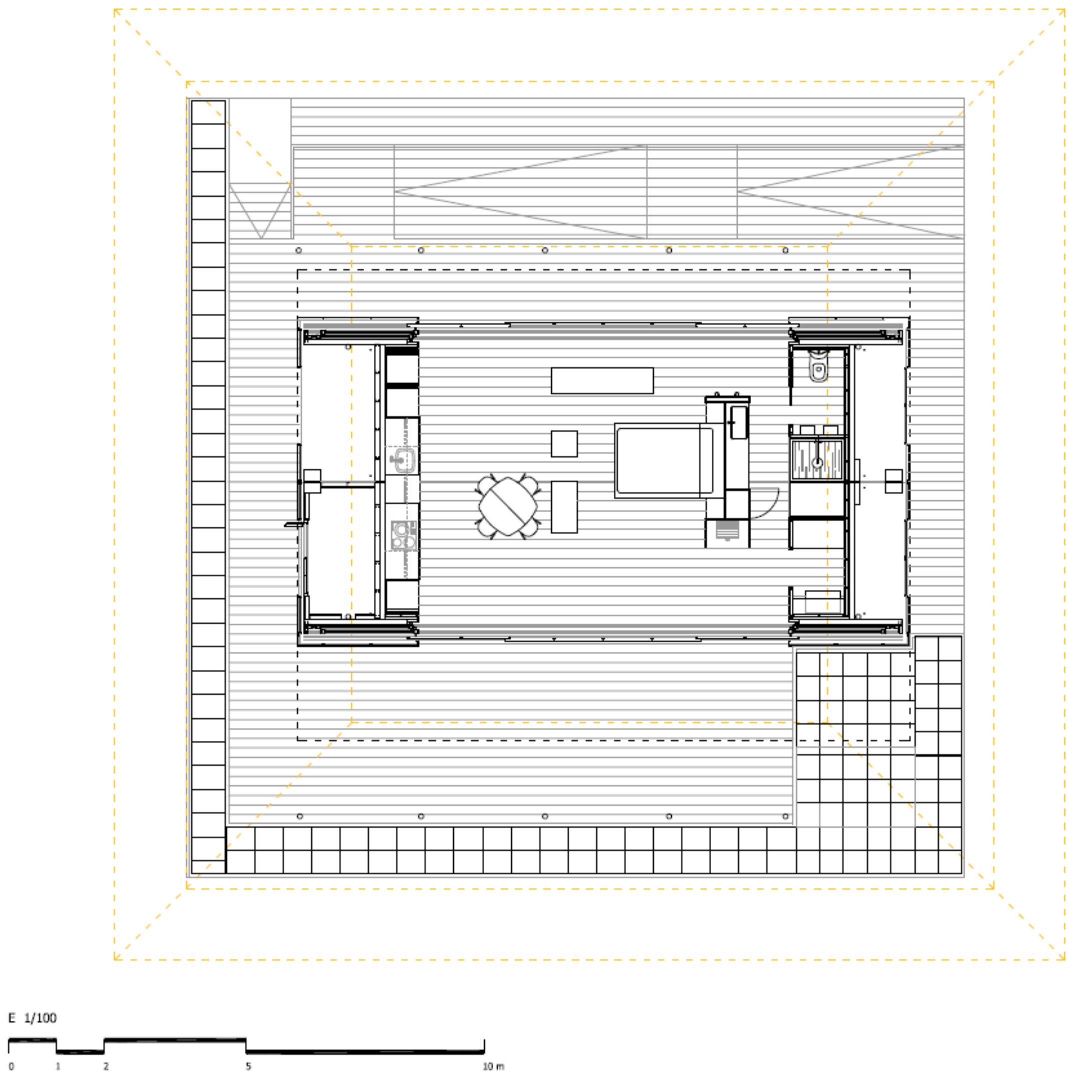


Figure 4: Bioclimatic chart of Madrid.

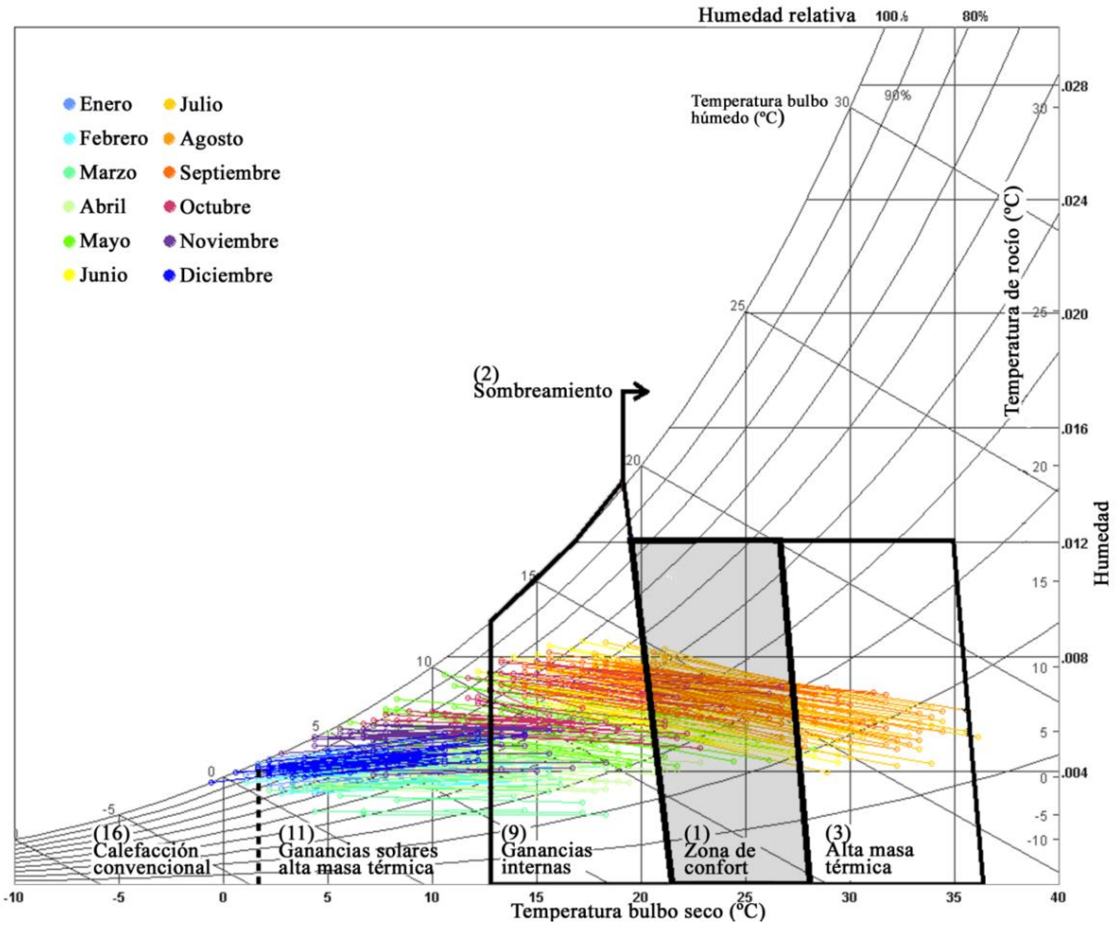


Figure 5: Passive strategies for summer. Shading and evaporative cooling if needed during the day and cross ventilation by removing northern and southern façades* PCM helps to control the interior temperature.

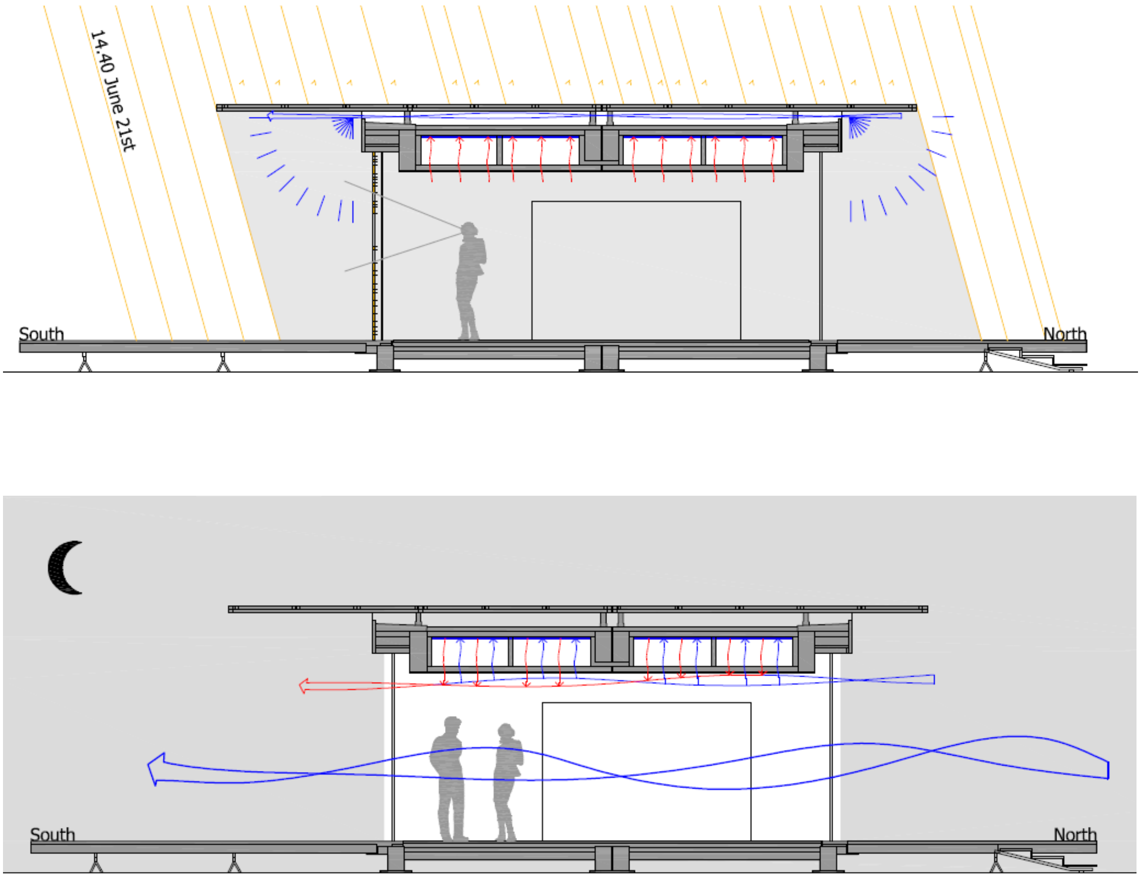
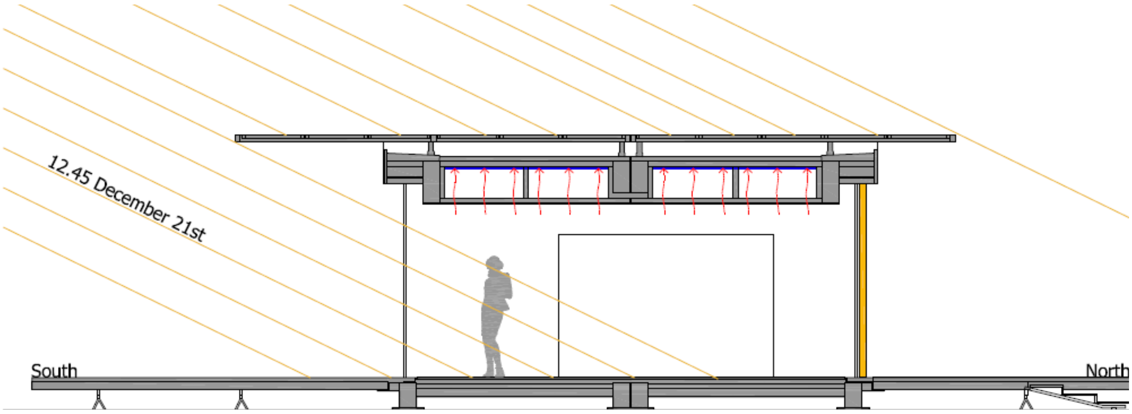


Figure 6: Passive strategies for winter. Solar exposure during the day and use of internal gains during the night. PCM helps to control the interior temperature.



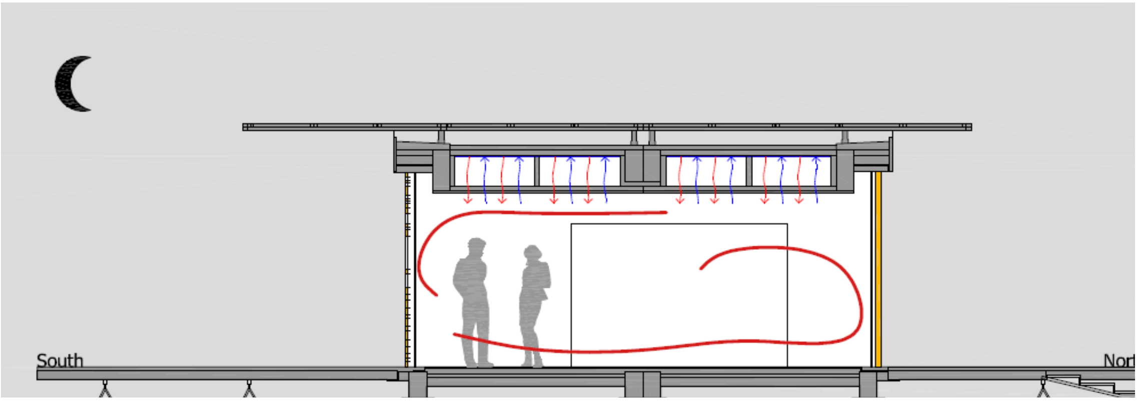


Figure 7: Installation of PCM panels in the ceiling.

Figure 8: Simulation of heating demand [kWh/m^2] for the five models.

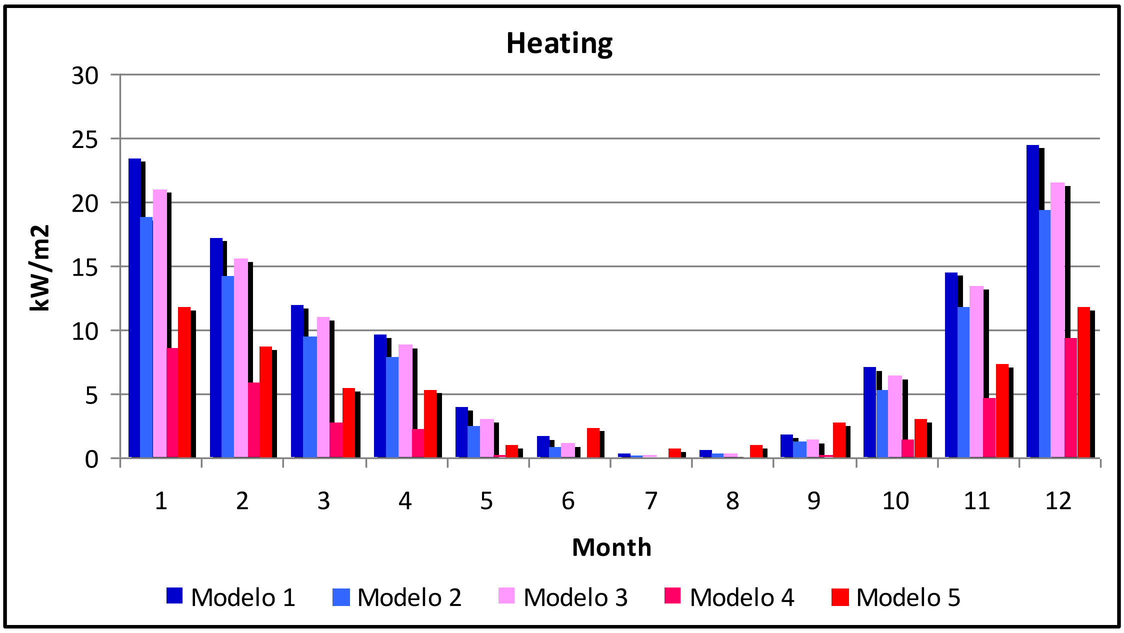


Figure 9: Simulation of cooling demand [kWh/m^2] for the five models.

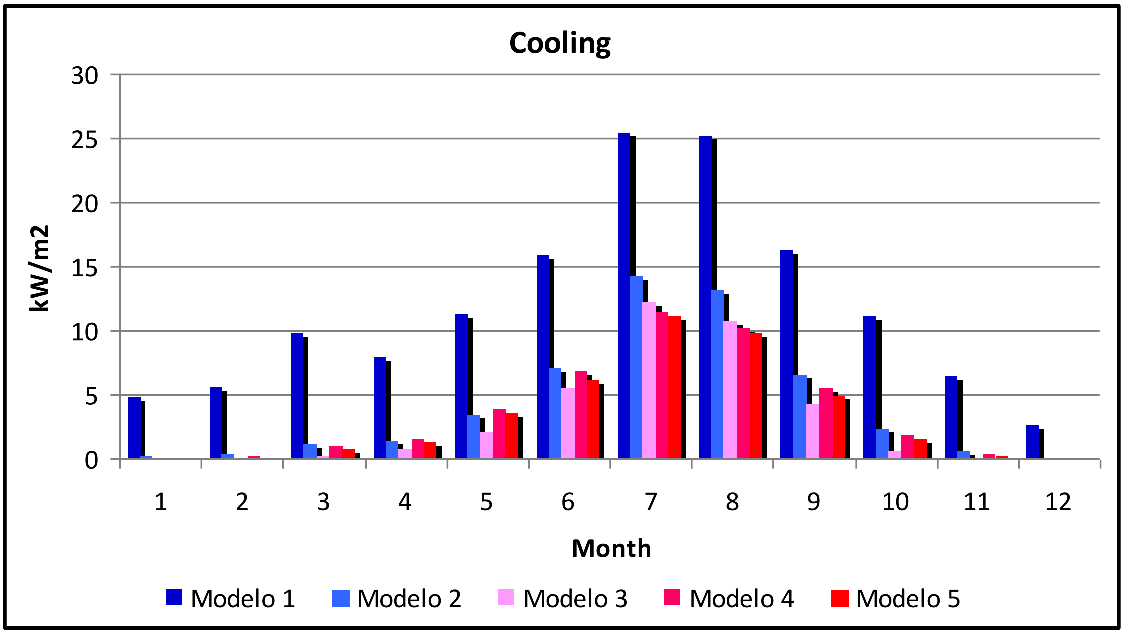


Figure 10: Structural components of the house.

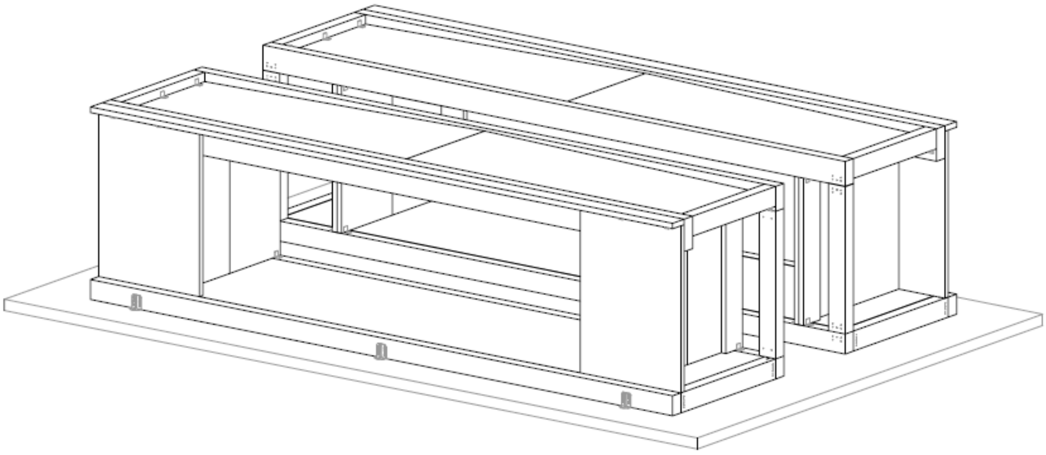


Figure 11: Construction blow up of the house.

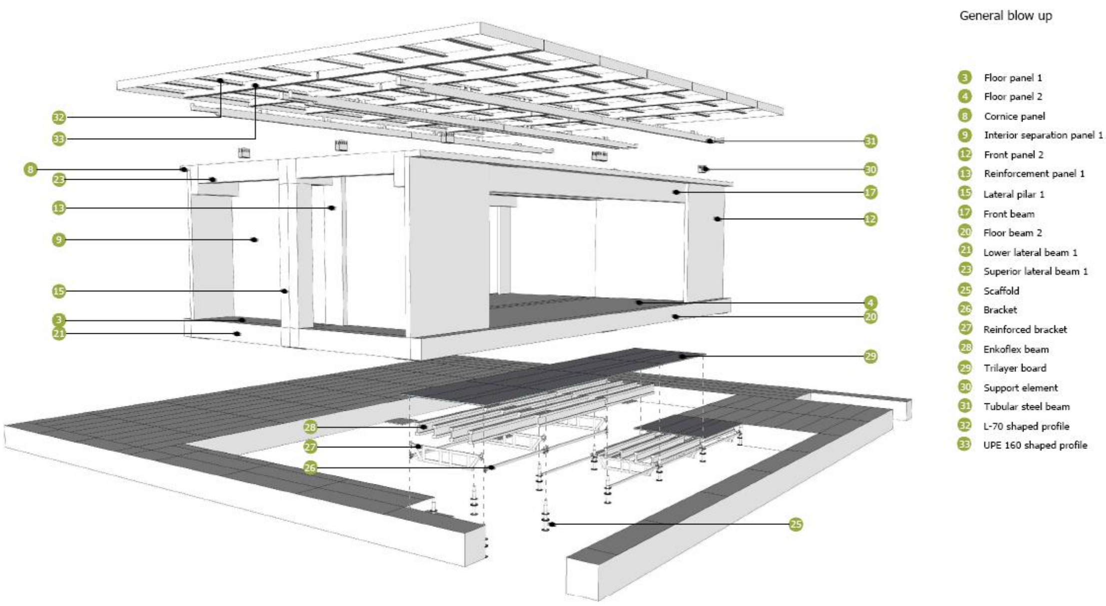


Figure 12: Scheme of active systems of the house

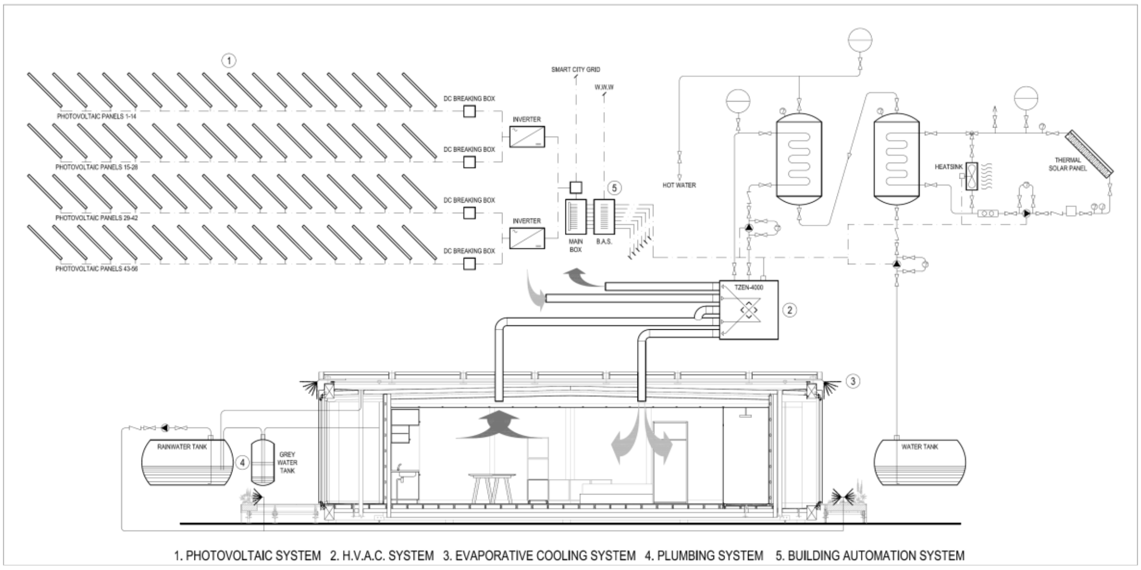
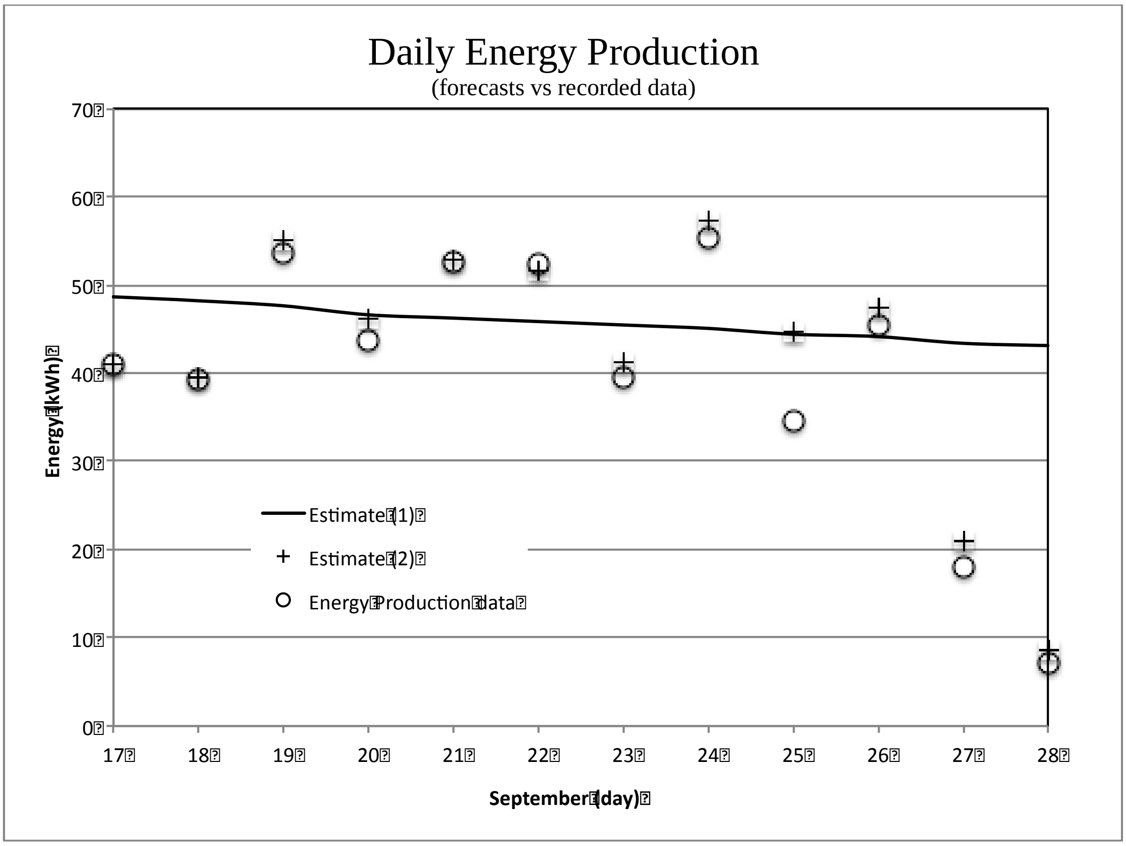


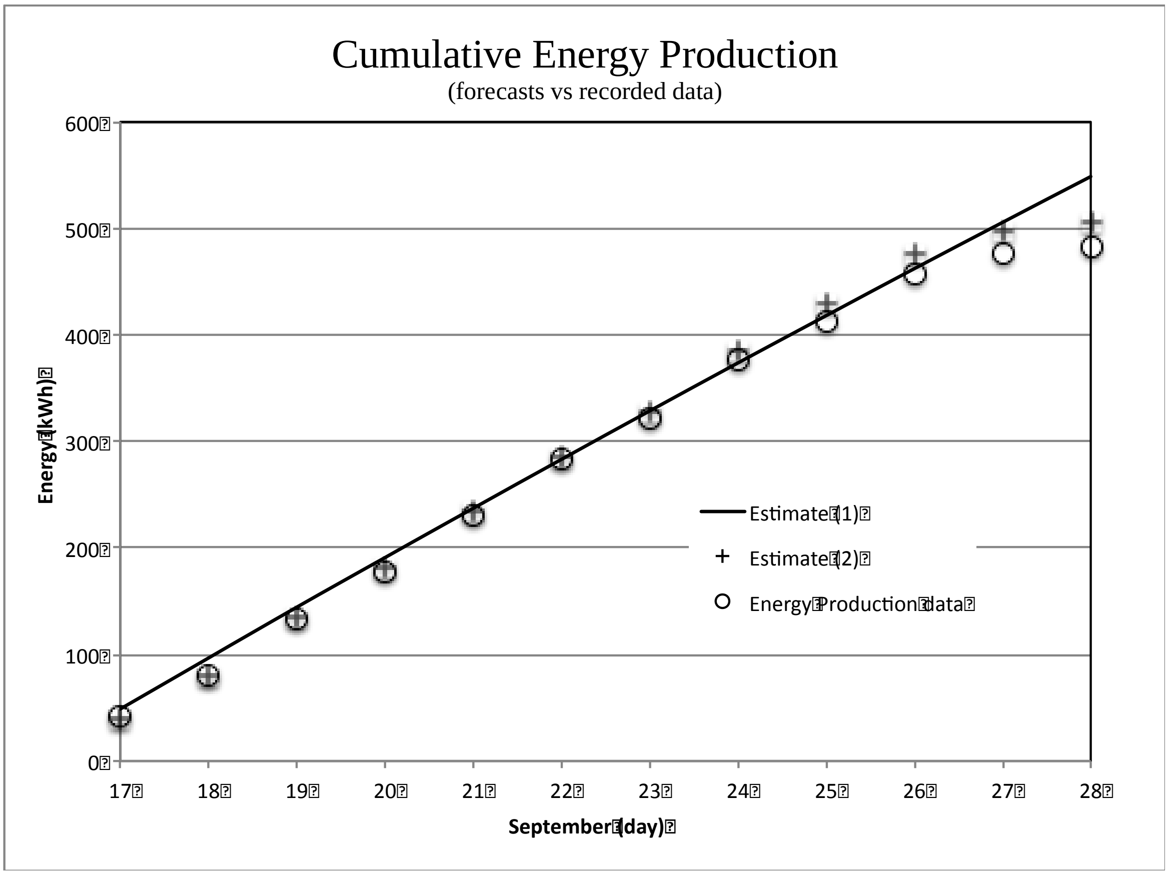
Figure 13: PV Roof of Ekihouse

Figure 14: Daily energy production of the photovoltaic system



.

Figure 15: Cumulative energy production of the photovoltaic system[†]



[†] An exception should be made concerning the data for September 27th and 28th because of the adverse weather conditions

Figure 16: Error vs Wind speed

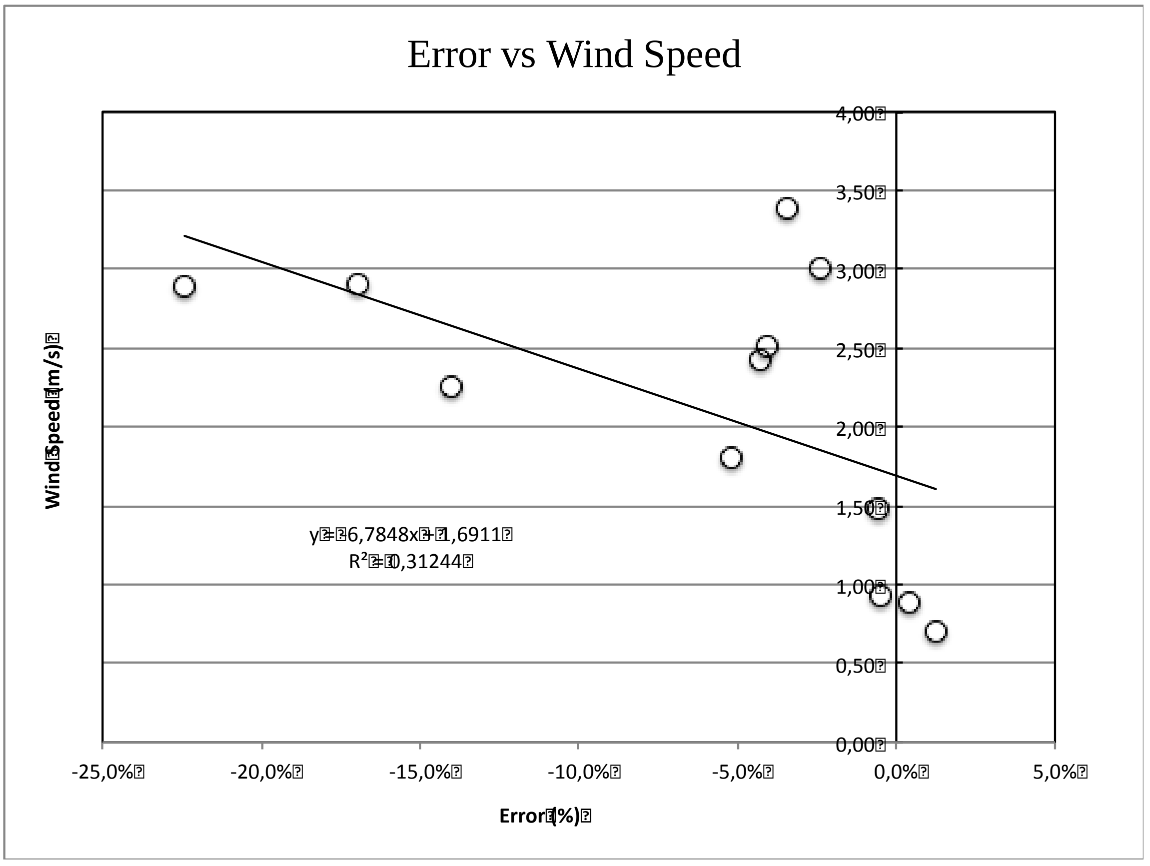


Figure 17: Transport and assembling

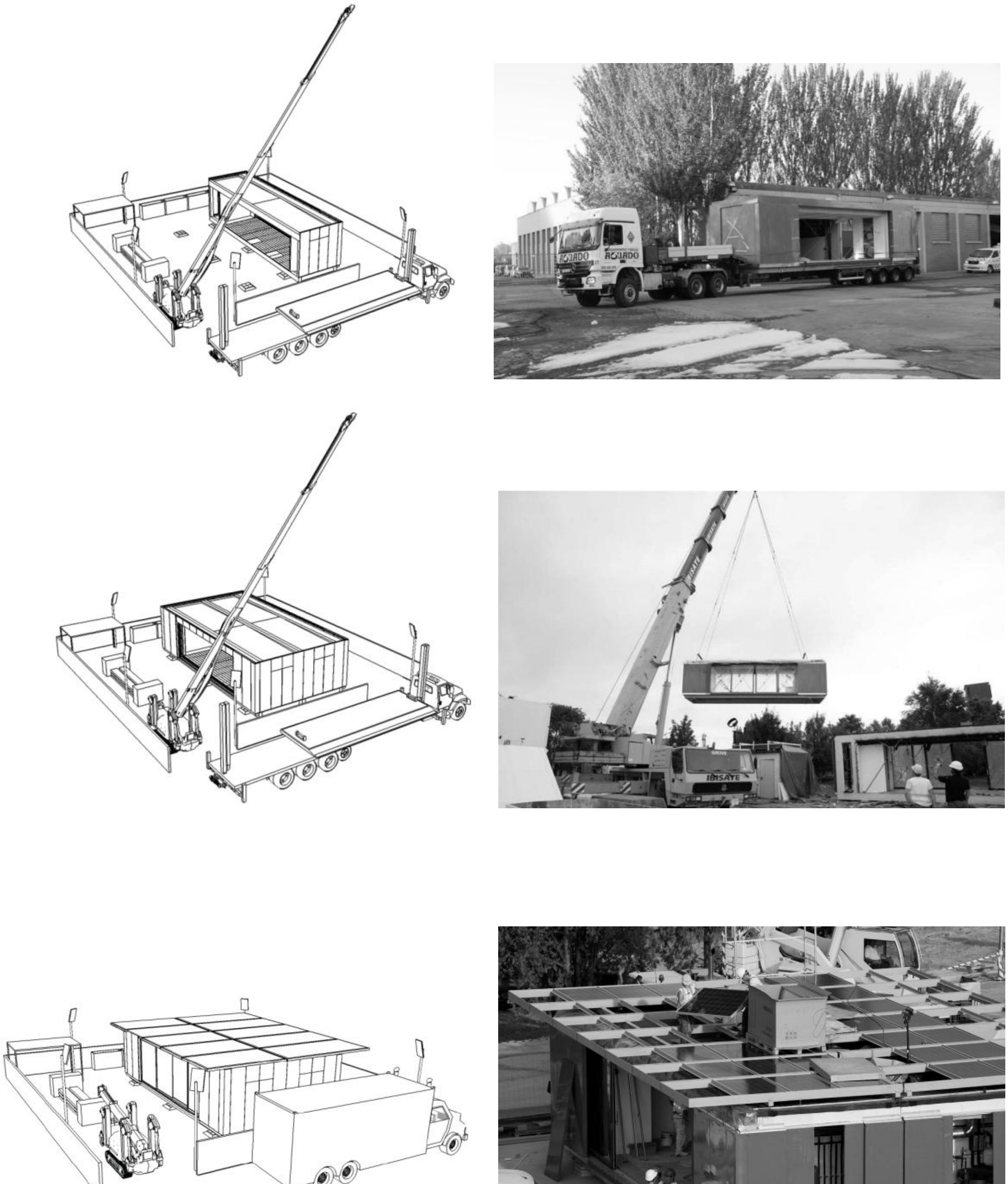


Figure 18: Grouping options of Ekihouse

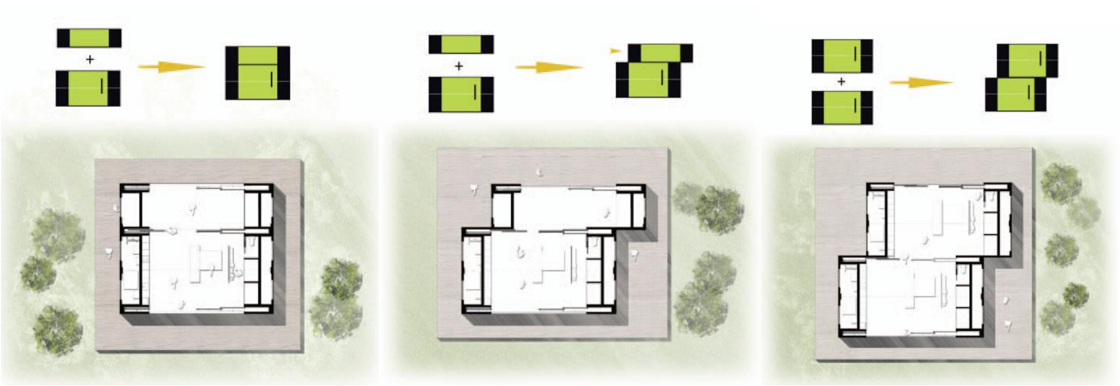


Figure 19: Oudoor/Indoor Humidity in competition week

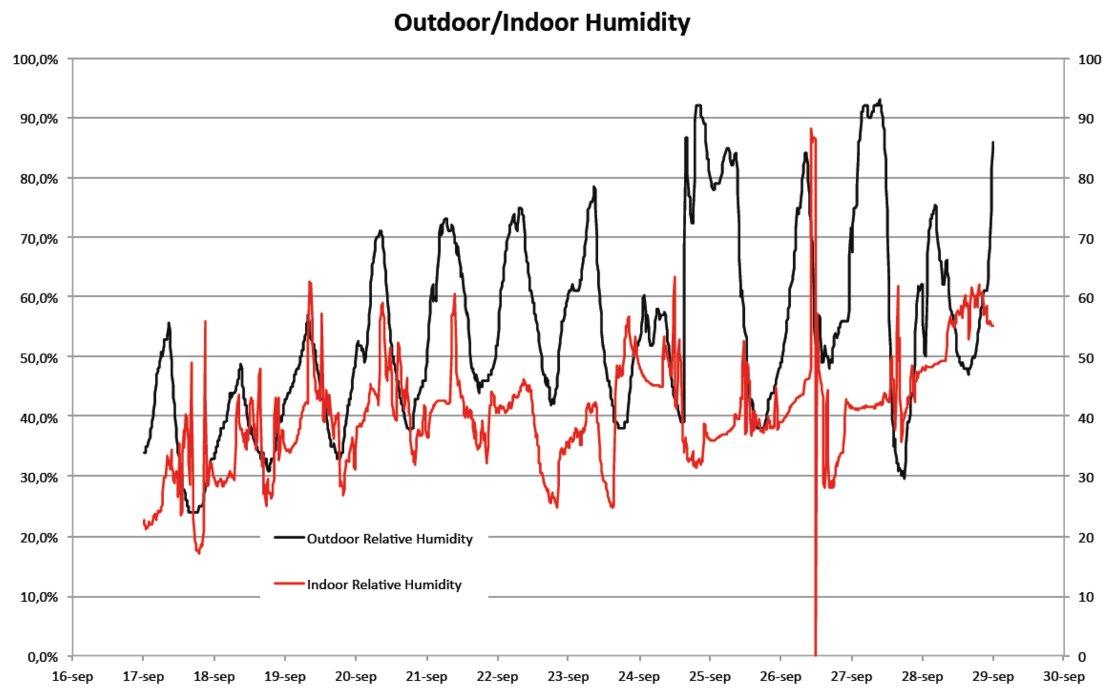


Figure 20: Oudoor/Indoor Humidity in competition week

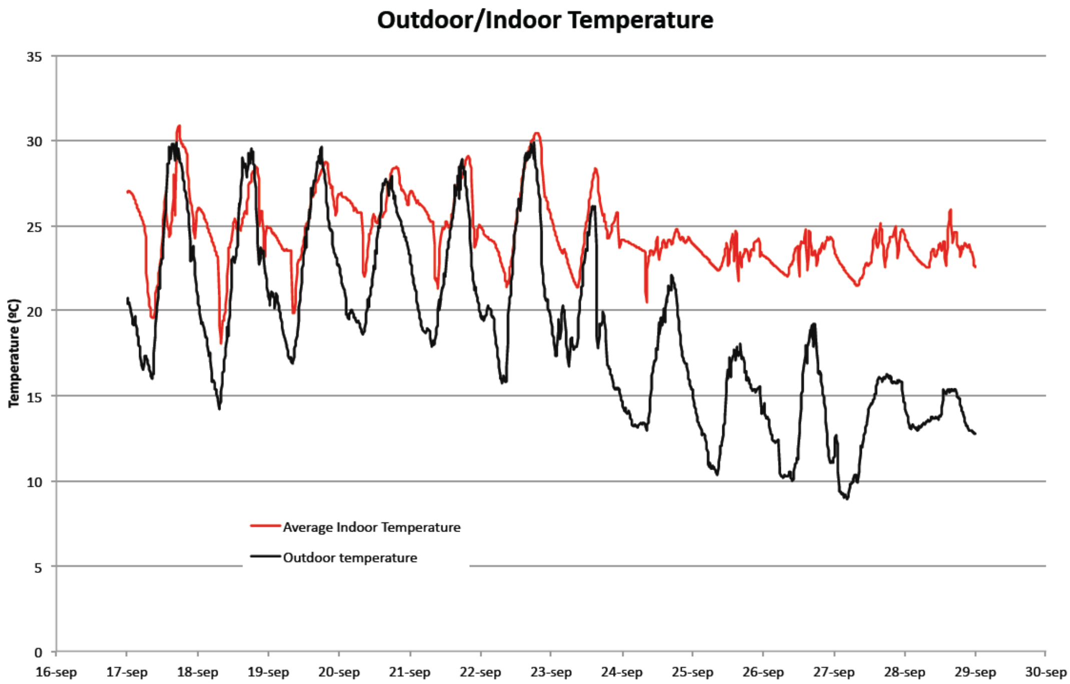


Figure 21: Interior view of Ekihouse

Figure 22: Ekihouse Team

Table(s) with Caption(s)

Table 1: Resume of systems and patterns of ventilation in the third, fourth and fifth model

.MONTH	Model 3	Model 4	Model 5
	Mechanical ventilation	**Without ventilation**	**Natural ventilation**
	Vol/h	Vol/h	Vol/h
January	0,89	0,00	0,51
February	0,87	0,00	0,68
March	0,93	0,00	0,93
April	0,92	0,00	1,09
May	1,00	0,00	1,31
June	1,00	0,00	3,08
July	1,00	0,00	1,53
August	1,00	0,00	2,48
September	1,00	0,00	2,60
October	0,96	0,00	0,98
November	0,89	0,00	0,71
December	0,88	0,00	0,34

Table 2: Electrical specification for the PV panels.

Electrical specification for the PV modules	ATERSA 214-P
STC rated output (Pmpp)	214 Wp
Short circuit current (Isc)	8,03 A
Open-circuit voltage (Voc)	36,02 V
Rated current (Impp)	7,38 A
Rated voltage (Vmpp)	28,99 V
Temperature coefficient β (Isc)	0.04 %/ºC
Temperature coefficient χ (Uoc)	-0.32 %/ºC
Temperature coefficient α (Pmpp)	-0.43 %/ºC
Normal Operating Cell Temperature (NOCT)	47ºC +/-2%

The PV installation of the Ekihouse is a grid-connected system with a theoretical power peak of 11,98 kW, comprising 2 inverters and 56 solar panels arranged in 4 strings of 14 modules each. The individual PV modules contain 60, 156x156 mm polycrystalline silicon cells in series, with a module efficiency of h=13,14%.

Table 3: PV Energy production Wh

PV ENERGY PRODUCTION Wh

	September											
	17	18	19	20	21	22	23	24	25	26	27	28
Estimate (1)	48644,53	48202,73	47614,46	46607,84	46235,42	-	-	45055,56	44397,71	44129,83	43370,24	43108,81
Estimate (2)	40877,68	39413,21	55015,39	46147,59	52800,36	51634,10	41229,49	57349,85	44587,51	47470,44	21002,92	8684,46
Empirical values	41038,53	39211,31	53712,77	43767,41	52495,41	52276,49	39555,54	55377,98	34593,92	45432,79	18057,63	7212,12

(1) Estimation using last 10 years data for irradiance, wind speed and temperature

(2) Estimation using measured values for irrandiance, wind speed and temperature during the contest periode

Table 4: Difference between energy predicted production values and data recorded

Difference between energy predicted production values and data recorded

	September											
	17	18	19	20	21	22	23	24	25 *	26	27	28
Error	0,4%	-0,5%	-2,4%	-5,2%	-0,6%	1,2%	-4,1%	-3,4%	-22,4%	-4,3%	-14,0%	-17,0%
Average wind speed (m/s)	0,88	0,93	3,01	1,80	1,49	0,71	2,51	3,39	2,89	2,42	2,25	2,91

* PV system offline incident

Table 5: Energy balance kWh.

ENERGY BALANCE kWh

	September											
	17	18	19	20	21	22	23	24	25	26	27	28
Energy produced	41,04	39,21	53,71	43,77	52,50	52,28	39,56	55,38	34,59	45,43	18,06	7,21
Energy absorbed	26,15	32,14	26,63	22,59	16,79	10,66	11,64	17,49	16,25	21,29	19,32	21,91
Daily balance	14,89	7,07	27,09	21,18	35,71	41,61	27,91	37,89	18,34	24,14	-1,27	-14,69
Cumulative	14,89	21,96	49,05	70,23	105,94	147,55	175,46	213,35	231,69	255,84	254,57	239,88

Table 6: Energy production/consumption correlation.

ENERGY PRODUCTION/CONSUMPTION CORRELATION

September											
17	18	19	20	21	22	23	24	25	26	27	28
0,49	0,51	0,56	0,64	0,85	-	-	0,44	0,46	0,75	0,53	0,65

***Highlights (for review)**

-Full integration of active - passive solar technologies and passive design criteria to achieve an energy self-sufficient house.

-Strong points of the project: the potential of energy production, adaptability, flexibility, capacity of passive strategies to respond to external conditions achieving hygrothermal comfort and energy self-sufficiency.

-Ekihouse has five active systems to maintain the comfort level of the inner space: Photovoltaic system, HVAC system, Evaporative Cooling system, Plumbing system and Building Control system.

-Industrializable and timber based modular construction.

-