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# Sustainable design of near zero energy buildings

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## ABSTRACT

In recent decades, particular attention has been paid towards energy savings in buildings, as the energy consumption in building sector accounts for about 40% of total energy consumption in developed countries. Based on the new Energy Strategy, an energy-efficient building will have to cover its own needs in each season, and the energy consumption is to be reduced by more than a third by 2035 and nearly half by 2050. In the first stage of this study, a conventional building located in Zurich, Switzerland, was studied for designing photovoltaic-thermal systems and insulation with the aim of minimizing building energy consumption. Furthermore, an analysis of the reducing of the $CO_2$ emissions in urban area in Kuwait has also studied. The data was optimized with the payback calculations as a necessary optimality condition and resulted in four optimized values for each case. In the second stage, a non-insulated residential masonry building located in Switzerland which was affected by indoor mold exposure, considered as a real case-study. To create both horizontal and vertical barriers against lateral moisture penetration, "HP-K Pro" as a new insulation material was selected and injected into the identified problem areas of the walls. The coupled heat and moisture transfer relationship numerically calculated using the finite element software COMSOL Multiphysics, and the model was validated on the basis of experimental measurements. It was concluded that properly implementation of HP-K Pro-Insulation leads to well-sealed and well-insulated house, as well as lower initial expense and operating costs compared with the other conventional insulation materials. Therefore, if it can be used in porous material such as masonry walls, make an ideal solution for moisture-resistance insulation systems.

**Keywords:** ZEB (Zero Energy Building), Molding, Optimal Moisture-resistance Insulation system, COMSOL Multiphysics, $CO_2$ emissions

## 1. INTRODUCTION

Nowadays, the energy crisis is one of the controversial issues around the world. Plundering fossil fuel recourses from one hand and some environmental problems such as global warming from another hand have led nations to establish policies to control harvesting the recourses and preserve them for subsequent generations. Hence, by 2020, the EU (European Union) aims to reduce its greenhouse gas emissions by at least 20%, increase the share of renewable energy to at least 20% of consumption, and achieve energy savings of 20% or more. Regarding the fact that the largest energy end-use in Switzerland belongs to the residential sector, it seems necessary to analyze the energy flow in the buildings. Fig. 1 illustrates the residential energy consumption by end-use in 2015. It is evident that the most amount of energy is being consumed for space heating (67%) and then, water heating and appliances (14%). Therefore, we can come to the conclusion that saving energy in space heating as well as using renewable energies to supply electricity might be reasonable ways to achieve EU's goals in this country [1-4].

The Swiss Federal Office of Energy (SFOE) and most other European countries have set specific targets in order to maximize building energy efficiency and reduce $CO_2$ emissions in future. In 2015, oil was used as the primary energy source and accounted for 44% of all energy used in Switzerland. The second largest energy demand was for coal, followed by natural gas and nuclear energy [5,6] Due to increasing oil tax rates, The Swiss Energy Strategy (2050) maps the way towards a low-carbon economy in which energy sources shift from oil to renewable energy sources such as hydropower, natural energy and geothermal energy. The Efficient World Scenario (EWS) highlights the potential for global building energy demand to decline between now and 2040, despite total building floor area growing by a further 60%. On average, buildings in 2040 could be nearly 40% more energy efficient than today. Among available energy resources, solar energy is of specific importance due to extensive availability and lower costs, compared to other renewable resources. There are various factors which can affect building energy consumption. Some of them are: building type, construction year, construction material, thermal insulation, location, climate, as well as the implementation of energy efficient technologies [7-9].

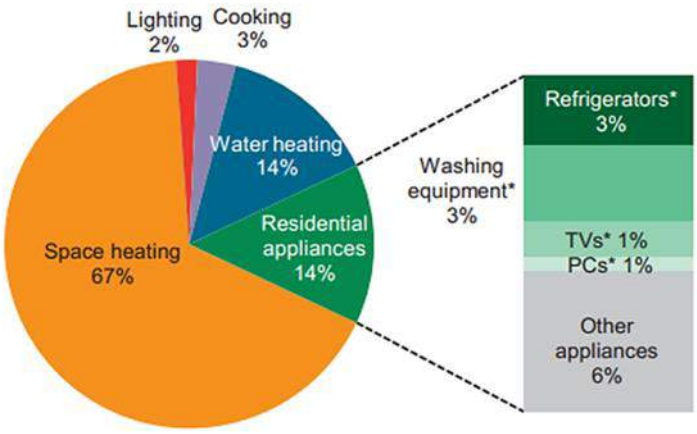



Fig. 1 The residential energy consumption by end-use

There are various methods to reduce the use of conventional energy from fossil fuels to meet the energy requirement for the building. The combination of various solar passive design aspects can easily be integrated in new buildings based on the site, orientation of building and local climatic conditions. In this case, the heat and electricity loads were investigated in a conventional house located in Zurich, Swaziland (Fig. 2). Three applicable

scenarios have been proposed in order to save energy in space heating sector. The scenarios are taken in to account technically and economically and then, the best one is identified to be implemented. Moreover, employing renewable energies, specifically, solar photovoltaic (PV) systems to supply electricity is considered. For the required electricity load of the considered building, the proper PV system configuration is designed and an economic analysis is conducted in advance. In many cases the outdoor temperature has been considered as the major influencing factor. Thus, a heating design software (TiSoft) was used to investigate the effectiveness of same insulations system in the hot climate areas such as Kuwait.

Fig. 2 The building exterior of the case study in Zurich [June 2017]

This paper also presents a study examining how the planning and building system is providing a sustainable built environment to urban cities, despite the gap between them. Energy consumption per capita in Kuwait is among the highest in the world. This is caused by a high standard of living, harsh summer climatic conditions, which necessitate cooling, highly subsidized energy costs, and rapid economic growth. Kuwait's climate is classified as dry, hot, with long summers, and short winters. As the relative humidity increases, the temperature sometimes exceeds 50 ºC in the shade. Kuwait's increasing population and the response to it is a main contributor to the problems of energy consumption. This continuous increase in population, with an average growth rate of 3.3% [Kuwait Central Statistical Bureau, 2018], contributes highly to the energy consumption in the country. Other factors contribute to this problem of increasing energy consumption as well. One is the significant amount of waste and over-consumption of energy, which adds to the insufficiency of the energy supply. The consumption of electrical energy per capita was 13,530 KWh during 2013 [MEW Statistical Yearbook, 2014]. In summer, air conditioning systems consume nearly 70% of the peak load demand and 45% of the annual energy consumption [Kuwait Code MEW R-6-2014] as they are the biggest silent energy users in residential buildings. Energy consumption and carbon dioxide emissions worldwide are increasing at alarming rates. Both low-rise buildings and high-rise buildings are the major users of energy

consuming 40-50% of primary energy. Building usage results in approximately 40% of $CO_2$ emissions.

The building envelope is the parts of a building that shapes the primary thermal barrier between interior and exterior. These parts greatly influence the energy consumption of a building. In this study, the four parameters of U-Wall, U-Roof, U-Window, and SHGC will be focused onto determine the annual energy consumption of a residential and commercial buildings in Kuwait. Thickness of the walls and roof layers will be studied to see their effect on energy consumption. Windows and fenestration systems of a building play an important role in energy saving development and sustainability of the building; therefore, these will be studied. In this research, optimization is described as to how to quantify and implement energy performance solutions in residential and commercial buildings in Kuwait. This in turn will help to determine where and to what degree of the total annual energy (KWh) is wasted.

Kuwait is committed in the development of projects, including the establishment of several mega residential cities, with the implementation of modern specifications for sustainability in all housing projects. South Mutla is the largest residential project in the history of Kuwait comprising integrated housing projects. It includes around 28,363 residential plots and 600 service buildings. It is one of the most recent residential projects that has been introduced in Kuwait, with an expected occupancy of 400,000 people.

## 2. HEATING LOADS IN THE BUILDING

The heating loads (heat losses and water heating) have to be considered to assess the energy demand of the building sector. Generally, the heat loss of a building falls into two main categories: 1) Wall and roof heat loss, and 2) Air infiltration heat loss.

### *2.1 Wall and roof heat loss*

The heat transfer from building envelop has been known as the main part of the heat loss in the building. Owing to the insulation of the floor in the considered building, the heat loss has been calculated for walls, roof, doors and windows. Table.1 depicts the estimated heat loss from walls, windows, doors and roof with regard to their area and heat transfer coefficient, based on building heating load calculation references. It should be noted that the input data were somehow limited and consequently, the acquired results are considered to be an estimate. Further detailed results require a complete set of building information.

Table.1 Envelop heat loss from the building

| Envelop Heat loss | Wall | Roof | Doors | Windows |
|---|---|---|---|---|
| Area ($m^2$) | 125.71 | 139.37 | 2 | 25.62 |
| Heat transfer Coefficient ($W/m^2$. °C) | 2.5 | 0.8 | 1.8 | 2.26 |
| Ideal room temperature (°C) | 20 | 20 | 20 | 20 |
| Outside temperature (°C) | 13 | 13 | 13 | 13 |
| Temperature difference (°C) | 7 | 7 | 7 | 7 |
| Heat loss (KW) | 2.2 | 0.78 | 0.0252 | 0.4054 |

The overall heat loss from the envelop equals 3.47 [KW] which is consistent with the annual oil consumption and hence, the calculation procedure is verified. As mentioned, more accurate results require an extensive set of detain input data.

### *2.2 Air infiltration heat loss*

The stack effect and wind flow velocity cause air infiltration in buildings. The leakage air flow rate depends on the air sealing of the building envelope, windows as well as the

building height. In order to assess the heat loss, the amount of airflow has been calculated according to Eq. (1):

(1) $$V = v \times n,$$

In which $\boldsymbol{V}$, $\boldsymbol{v}$, and $\boldsymbol{n}$ represent the volume of air leakage, the volume of each space [m$^3$], and the number of air changes per hour, respectively. Furthermore, the air infiltration heat loss could be estimated by Eq. (2) as follows:

(2) $$Q_2 = V \times 1.20 \times 1009.02 \times (T_{Out} - T_{In}),$$

In which, air density and air heat capacity are assumed to be 1.20 [kg/m$^3$] and 1009.02 [J/kg. °C], respectively and $\boldsymbol{T_{out}}$ and $\boldsymbol{T_{In}}$ represent Ideal room temperature [°C] and Outside temperature [°C], respectively. It is calculated that the total air filtration heat loss equals 703.94 [W].

The summation of wall and roof heat loss as well as air infiltration heat loss is the total heat loss from the building. Moreover, a safety factor of 1.1 has been taken into account in order to increase the reliability. Therefore, the total heat loss is estimated to be 4482.55 [W], according to the following equation, Eq. (3):

(3) $$Q_{Total} = (Q_1 + Q_2) \times 1.1,$$

*2.3 Water heating energy*

In this part, domestic water heating energy consumption has been analyzed. The amount of hot water flow in the building has been calculated regarding home appliances consuming hot water (Kitchen sink, washing machine, dishwasher, Shower bath, and WC). Therefore, the energy consumption could be determined by Eq. (4), as follows:

(4) $$Q_3 = V \times 998.15 \times (T_{Outlet} - T_{Inlet}),$$

In which, $\boldsymbol{V}$, $\boldsymbol{T_{outlet}}$, and $\boldsymbol{T_{Inlet}}$ are hot water consumption [m$^3$/s], ideal hot water temperature [°C], and inlet temperature [°C], respectively. Also, the water density is assumed to be998.15 [kg/m$^3$]. According to the performed calculations, the energy consumption for water heating is acquired to be 366.36 [W]. Finally, the overall energy requirement is estimated to be 4850 [W] which is consistent with the annual oil consumption.

## 3. ENERGY SAVING INSULATION SCENARIOS

In order to save energy in the case study building, the insulation of walls and roof are investigated. The main features of the selected insulation for walls and roof have been presented in Table. 2 [3].

It is considered that the insulation area equals the walls or the roof area. Thus, the amount of saved energy is calculated based on three scenarios: 1) insulating walls, 2) insulating the roof, 3) insulating both of the roof and walls. Also, the cost and payback period as well as the saved amount of carbon emission for each scenario are estimated. The calculated results have been summarized in Table.3.

Table. 2 Properties of available insulations

| Type | Thickness (mm) | Thermal conductivity (W/m.K) | Price (CHF/m$^2$) |
|---|---|---|---|
| TETTO Alu | 80 | 0.022 | 24 |
| LAMBDA Vento | 120 | 0.031 | 31.7 |

Table. 3 The calculated results of using insulation for 3 scenarios

| Scenarios | Initial investment (CHF) | Estimated Construction Cost (CHF) | Saving Energy (Lit/year) | Saving money (CHF/Year) | Saving Carbon Emission (kg $CO_2$/Year) | Approximate payback period |
|---|---|---|---|---|---|---|
| Only insulating walls | 4180 | 75000 | 2113.44 | 2113 | 0.53 | 37 years |
| Only insulating roof | 3345 | 38000 | 263.68 | 263 | 0.10 | 157 years |
| Insulating walls & the roof | 7524 | 113000 | 2377.12 | 2377 | 0.63 | 50 years |

## 4. PHOTOVOLTAIC SYSTEM DESIGN FOR ELECTRICITY SUPPLY

### *4.1 PVsyst design*

According to the provided data, the total annual electricity consumption of the house equals 5680 kWh and the input data are assumed to be averaged over the year. The design software package, PVsyst, is used for conducting a rough-scale design for the system. For the Metrological data, the data acquired by the Chur station Metronome 7.1 (1991-2010) is used, which is located 90 km from the house site. It should be mentioned that a full design with accurate details requires some on-site measurements. Using the angle-optimizer of the software and based on sun-path diagram, a tilt angle of 38° and an azimuth angle of 1° due south, approximately yield the maximum insolation absorption throughout the year. Increasing the tilt angle will increase the summer insolation yield, while decreasing it will increase the winter yield. Based on the total annual demand and accounting for a reliability factor regarding system losses and weather conditions, a PV system with 4.8 kW of capacity is recommended by the authors to be installed. It should be noted that the recommended capacity is estimated with the assumption of zero shading on the roof, which should be further verified on site. Fig. 3 shows the designed system specs in PVsyst. The PV panel as well as inverter brands were selected based on the market availability, system compatibility, and required voltage and current, to the best of the authors' knowledge. Further market investigation is recommended. It is observed from the list that an array of 16‘300W panels, two strings of 8 panels in series, is appropriate demand-wise, which occupies an approximate space of 30 $m^2$ of roof space.

Fig. 4 depicts the approximate system loss, including array loss and DC-AC conversion loss, and the total useful energy (inverter output) for months of the year in kWh of production per nominal kW capacity of the system (4.8 kW) per day. Utilizing high-efficiency devices (both panel and inverter) will increase the total yielded energy, but increases the capital investment costs as well. Table. 4 further details these values along with some other useful ones, for the designed system throughout the year. It should be noted that the utility tariff is specified to be 0.3 CHF/kWh (constant), while the feed-in tariff, the price of selling the electricity back to the grid, is determined to be 0.1 CHF/kWh. Also, Fig. 5 shows the loss diagram over the year as well as the net system energy outcome. Table. 5 shows the list for the required system components, including PV panels, support and integration infrastructure, inverter, settings and wirings, grid-connection panel and controller, and grounding equipment, along with their average prices. Service costs and incentives including transport and assembly costs, engineering design cost, federal incentive subsidies, and tax on investment, are also listed and as a summation the gross investm ent

along with the net investment are calculated. It should be noted that the tax and incentive rates as well as service costs are estimated and explored to the best of the authors' knowledge and the respectful owner could change the values based on local regulations and calculate the accurate values.

| | | | | | |
|---|---|---|---|---|---|
| **Simulation parameters** | | System type | **No 3D scene defined** | | |
| **Collector Plane Orientation** | | Tilt | 38° | Azimuth | 1° |
| **Models used** | | Transposition | Perez | Diffuse | Perez, Meteonorm |
| **Horizon** | | Free Horizon | | | |
| **Near Shadings** | | No Shadings | | | |
| **PV Array Characteristics** | | | | | |
| **PV module** | Si-mono | Model | **Aleo P_19 / 300** | | |
| Original PVsyst database | | Manufacturer | Aleo Solar | | |
| Number of PV modules | | In series | 8 modules | In parallel | 2 strings |
| Total number of PV modules | | Nb. modules | 16 | Unit Nom. Power | 300 Wp |
| Array global power | | Nominal (STC) | **4800 Wp** | At operating cond. | 4361 Wp (50°C) |
| Array operating characteristics (50°C) | | U mpp | 231 V | I mpp | 19 A |
| Total area | | Module area | **26.3 m²** | Cell area | 23.6 m² |
| **Inverter** | | Model | **SUNString 5000** | | |
| Original PVsyst database | | Manufacturer | Sunset | | |
| Characteristics | | Operating Voltage | 125-400 V | Unit Nom. Power | 4.60 kWac |
| Inverter pack | | Nb. of inverters | 1 units | Total Power | 4.6 kWac |
| | | | | Pnom ratio | 1.04 |

Fig. 3 Designed systems specs extracted from the PVsyst software report

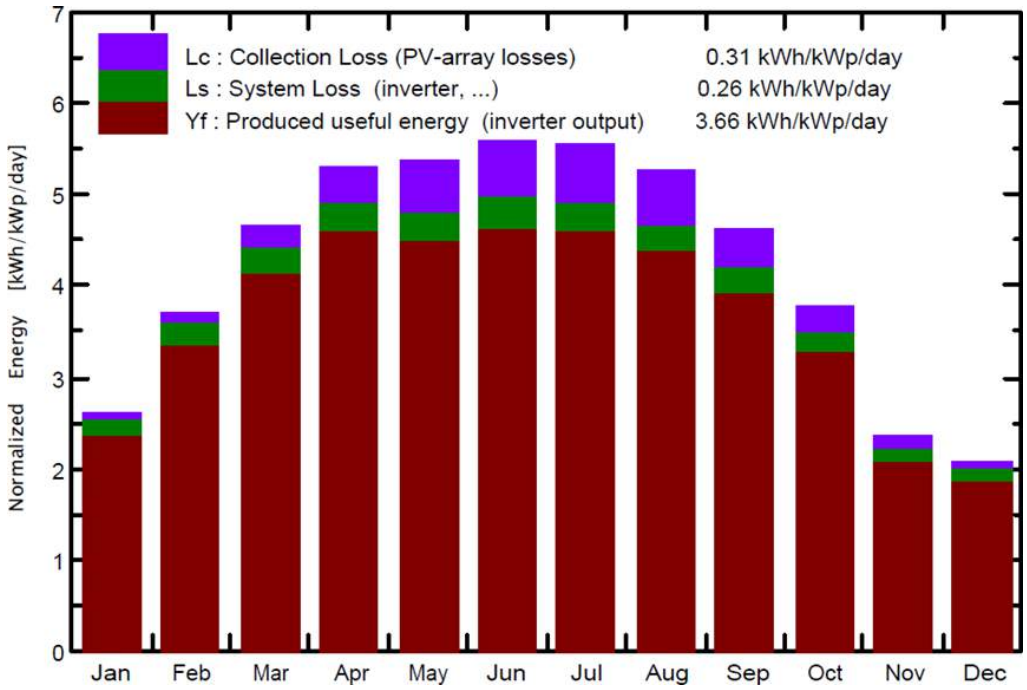



Fig. 4 Produced useful energy, system losses, and collection losses for months of the year

Table. 4 List of the designed system balances and main results extracted from PVsyst report

**Balances and main results**

| | GlobHor kWh/m² | DiffHor kWh/m² | T Amb °C | GlobInc kWh/m² | GlobEff kWh/m² | E Load MWh | E User MWh | E_Grid MWh |
|---|---|---|---|---|---|---|---|---|
| **January** | 41.4 | 19.59 | 0.53 | 80.8 | 78.8 | 0.477 | 0.186 | 0.170 |
| **February** | 63.3 | 31.19 | 2.11 | 103.3 | 100.7 | 0.431 | 0.219 | 0.237 |
| **March** | 107.5 | 49.74 | 6.20 | 144.6 | 140.7 | 0.477 | 0.254 | 0.365 |
| **April** | 141.1 | 63.46 | 10.31 | 158.9 | 154.2 | 0.462 | 0.261 | 0.403 |
| **May** | 168.3 | 71.63 | 15.12 | 166.3 | 160.8 | 0.477 | 0.271 | 0.400 |
| **June** | 177.2 | 85.08 | 18.04 | 166.6 | 160.5 | 0.462 | 0.274 | 0.396 |
| **July** | 177.4 | 83.21 | 19.08 | 171.1 | 165.2 | 0.477 | 0.282 | 0.405 |
| **August** | 150.9 | 71.15 | 18.71 | 162.4 | 157.3 | 0.477 | 0.271 | 0.382 |
| **September** | 111.0 | 48.97 | 14.66 | 138.8 | 134.9 | 0.462 | 0.242 | 0.326 |
| **October** | 77.7 | 39.65 | 11.01 | 116.7 | 113.6 | 0.477 | 0.238 | 0.254 |
| **November** | 41.5 | 21.84 | 5.46 | 70.5 | 68.7 | 0.462 | 0.155 | 0.146 |
| **December** | 31.9 | 17.22 | 1.57 | 64.3 | 62.5 | 0.477 | 0.167 | 0.115 |
| Year | 1289.2 | 602.72 | 10.28 | 1544.2 | 1498.1 | 5.618 | 2.819 | 3.598 |

Legends:

| | | | |
|---|---|---|---|
| GlobHor | Horizontal global irradiation | GlobEff | Effective Global, corr. for IAM and shadings |
| DiffHor | Horizontal diffuse irradiation | E Load | Energy need of the user (Load) |
| T Amb | Ambient Temperature | E User | Energy supplied to the user |
| GlobInc | Global incident in coll. plane | E_Grid | Energy injected into grid |

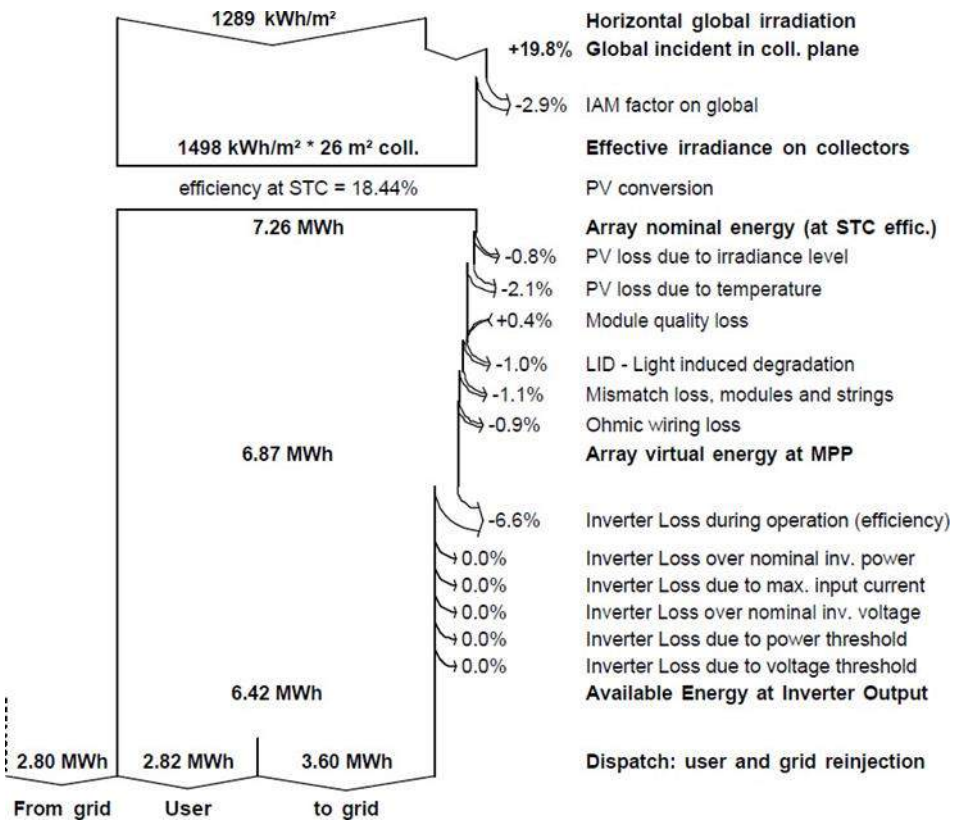



Fig. 5 System loss diagram over the whole year extracted from PVsyst produced report

Table. 5 Approximate average costs and investment for the designed system for the house in CHF (extracted from PVsyst report)

| **Investment** | | | |
|---|---|---|---|
| PV modules (Pnom = 300 Wp) | 16 units | 210 FS / unit | 3360 FS |
| Supports / Integration | | 69 FS / module | 1110 FS |
| Inverter (Pnom = 4.6 kW ac) | 1 units | 1100 FS / unit | 1100 FS |
| Settings, wiring, ... | | | 650 FS |
| Grid connection panel | | | 486 FS |
| grounding | | | 420 FS |
| Transport and assembly | | | 870 FS |
| Engineering | | | 2300 FS |
| Substitution underworth | | | 0 FS |
| **Gross investment** (without taxes) | | | **10296 FS** |
| **Financing** | | | |
| Gross investment (without taxes) | | | 10296 FS |
| Taxes on investment (VAT) | Rate 10.0 % | | 1030 FS |
| Gross investment (including VAT) | | | 11326 FS |
| Subsidies | | | -1800 FS |
| **Net investment (all taxes included)** | | | **9526 FS** |

The following notes should be taken into consideration regarding Table. 5 and the designed system:

• There are various PV cell manufacturers on the market with a broad range of warranties. The cells are selected based on the average German manufacturers' warranty, which is 25 years.

• There are also a broad range of inverters on the market with various performance features. The assumed cost in Table. 5, is for an inverter which has noise isolation embedded inside, omitting the requirement of a separate isolation transformer. The life-span of the inverter should also be considered in cost evaluations, which in our case it is considered to be 20 years.

• The government incentive plan is taken to be 0.375 CHF per watt of roof-mounted PV system installation according to Swissgrid utility company manuals. Further loan options could also be considered in economic evaluations.

Finally, the $CO_2$ emission is estimated in PVsyst according to IEA Standard values. Based on the system calculations, a cumulative emission value of 3.7 tons of $CO_2$ could be saved over a 30 year life span in case of installing the designed PV system, which could be beneficial in preventing further $CO_2$ production fines according to local regulation. Table. 6 and Fig. 6 show a $CO_2$ balance along with calculated values extracted from PVsyst produced report.

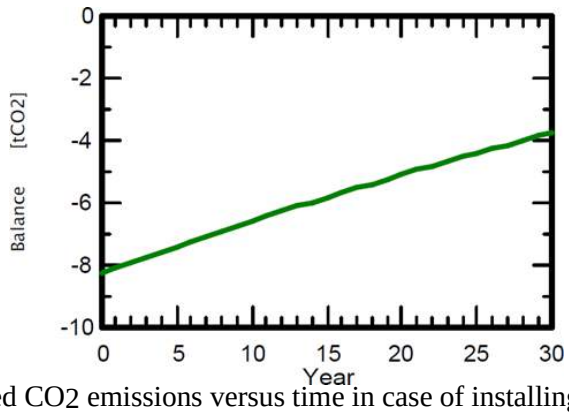



Fig. 6 Saved CO2 emissions versus time in case of installing the designed PV system

Table. 6 $CO_2$ balance for the designed PV system according to IEA standards (extracted from PVsyst report)

| | | | | |
|---|---|---|---|---|
| **Main system parameters** | System type | **Grid-Connected** | | |
| PV Field Orientation | tilt | 38° | azimuth | 1° |
| PV modules | Model | Aleo P_19 / 300 | Pnom | 300 Wp |
| PV Array | Nb. of modules | 16 | Pnom total | **4800 Wp** |
| Inverter | Model | SUNString 5000 | Pnom | 4600 W ac |
| User's needs | Daily household consumers | Constant over the year | Global | 5618 kWh/year |

| | | | | |
|---|---|---|---|---|
| **Produced Emissions** | **Total:** | **8.25 tCO2** | | |
| | Source: | Detailed calculation from table below | | |
| **Replaced Emissions** | **Total:** | **5.2 tCO2** | | |
| | System production: | 6416.47 kWh/yr | Lifetime: | 30 years |
| | | | Annual Degradation: | 1.0 % |
| | Grid Lifecycle Emissions: | 27 gCO2/kWh | | |
| | Source: | IEA List | Country: | Switzerland |
| **CO2 Emission Balance** | **Total:** | **-3.7 tCO2** | | |

**System Lifecycle Emissions Details:**

| Item | Modules | Supports |
|---|---|---|
| LCE | 1713 kgCO2/kWp | 0.18 kgCO2/kg |
| Quantity | 4.80 kWp | 160 kg |
| Subtotal [kgCO2] | 8221 | 28.8 |

*4.2 HOMER EXPERT economic analysis*

For a more detailed economic analysis, the designed system was also simulated in HOMER EXPERT, the renewable energies simulation software. Fig. 7 depicts the contour of PV system output in kW for daily hours during the year. Furthermore, Fig. 8 depicts the contours for the optimum grid purchase-sellback values in kW for daily hours throughout the year.

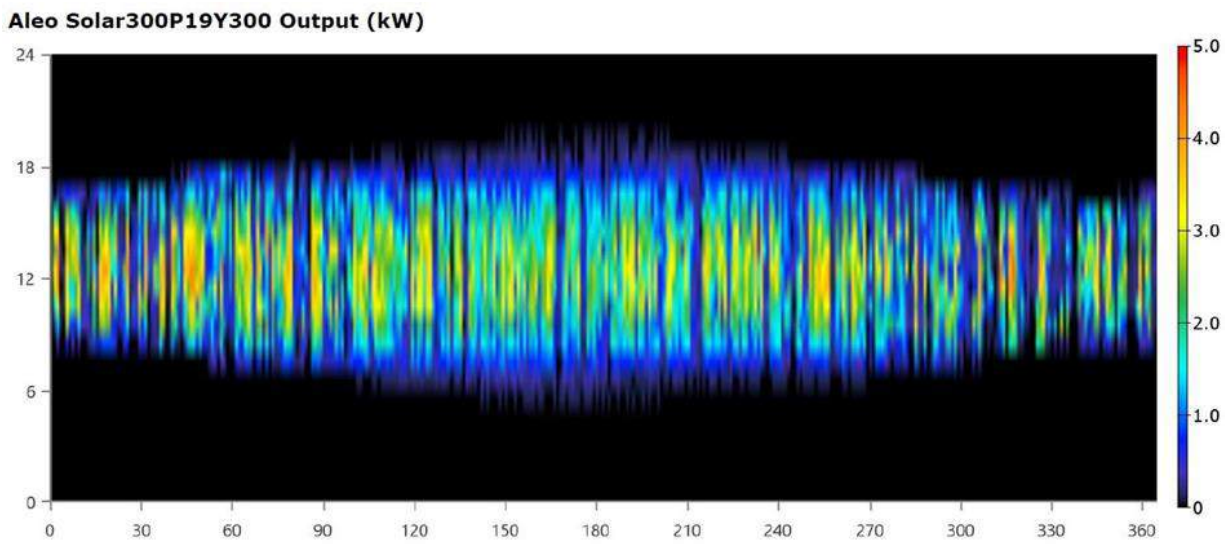



Fig. 7 PV system output power in kW during daily hours throughout the year

Table. 7 lists the major economic values estimated for the PV installation project including the present worth and annual worth in CHF, return on investment and internal rate of return percentages, and simple payback as well as discounted payback in years. For the economic calculations' input, the inflation rate and discount rate was determined to be 1.1% and 0.5% acquired from Switzerland financial reports and the life span of the whole project has taken to be 30 years. An approximate 9 year payback period makes further investigation and thorough economic evaluation a recommendation. It should be noted that in the calculation of this value, the possible carbon fines predicted to be imposed in the future are neglected.

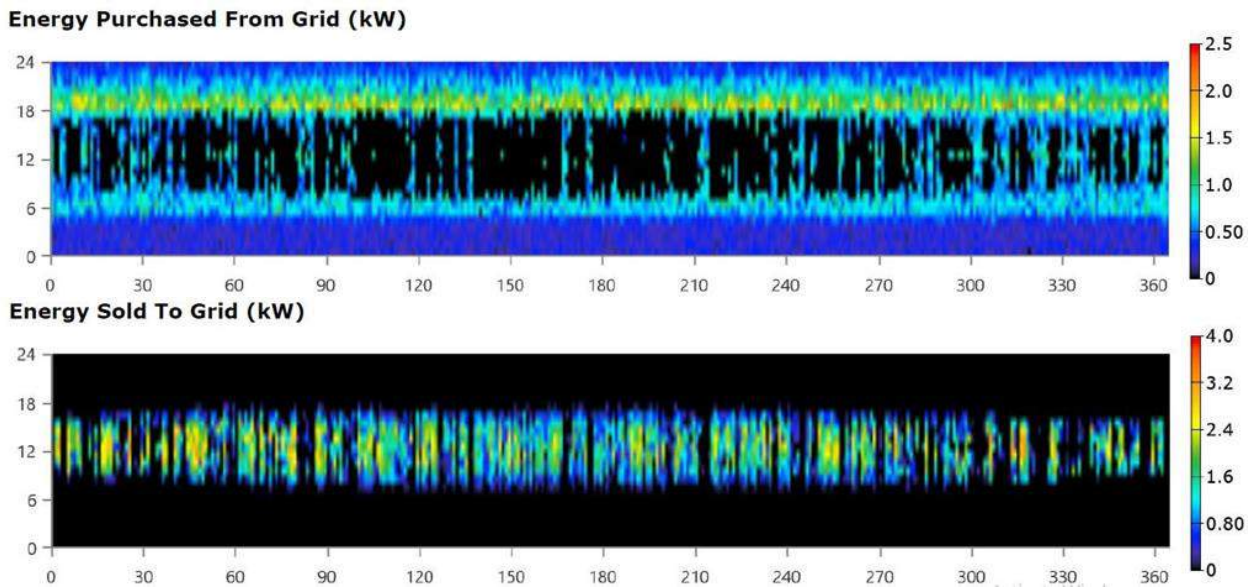



Fig. 8 Optimum combination for grid purchase-sellback power during the daily hours throughout the year for the battery-less scenario

Table. 7 Major economic metrics for the PV installation project for a 30-year life span for the battery less scenario

| Metric | Value |
|---|---|
| Present worth (CHF) | 14361 |
| Annual worth (CHF) | 613 |
| Return on investment (%) | 11.3 |
| Internal rate of return (%) | 10.4 |
| Simple payback (yr.) | 8.8 |
| Discounted payback (yr.) | 8.6 |

Finally, Fig. 9 depicts the cumulative discounted cash flows in CHF versus the system life span extracted from HOMER EXPERT produced report. The base case is the current state of the house and the current system represents the designed PV system. The approximate 9 year payback period is observed from this figure as well.

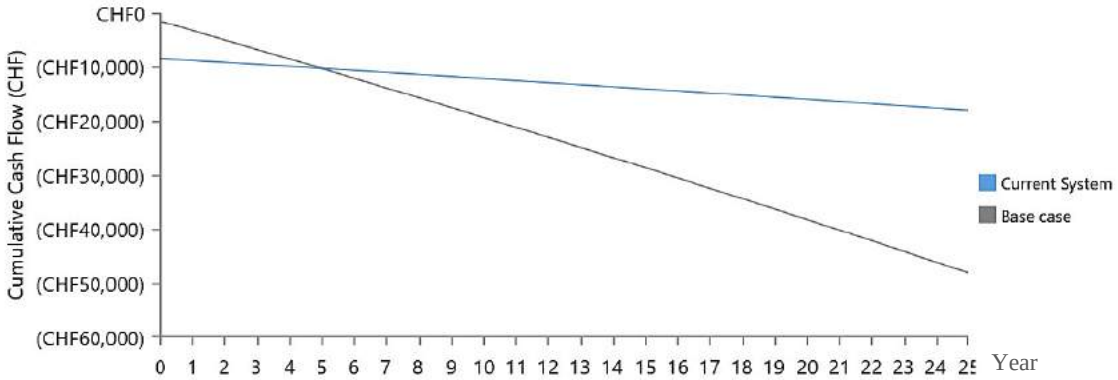


Fig. 9 PV system installation project cumulative discount cash flows over the system life span

*4.3 Required maintenance measures*

Provided that high-quality panels along with properly synched electrical equipment are selected and installed, the system requires not much of maintenance effort in the future. The only required measure is washing the PV panel surfaces with a washing hose approximately every six months (very dependent on-air pollution and weather conditions). However, extreme caution should be dedicated to proper system installation. High voltages of DC power could set the house on fire if improperly and carelessly worked with. Therefore, only specialized electrical technicians in this field are qualified for the job of installation. Proper availability of fire extinguishing equipment is also recommended for PV system life span, specifically for building integrated designs [10,11].

If any modifications or rebuilding of the roof is predicted to be required for the next 15 years (both aesthetically and strength -related), it must be conducted prior to PV installation, since the system is typically designed for at least 20-25 years and any roof replacement or fixation before this time period will waste the considerable installation capital costs.

*4.4 Battery backup scenario*

Typically lead-acid batteries are used for residential solar system applications. Ordinary batteries have 3-5 years of life span and should be replaced afterwards. It may also require regular maintenance efforts. Considering the technical, economical, and maintenance considerations, in case of an existing reliable grid connection, which is the case of our investigation, battery installation is only advised for the following situations:

a) If the utility service imposes time-of-use rates: In this situation, electricity will cost more during “peak hours” when demand for electricity is high, typically in the late afternoon and evening, and it will cost lower during the daytime when home electricity use is lower and solar panels are producing at the highest capacity. In these cases, home energy storage by using electricity from solar batteries during peak hours when utility electricity rates are at their highest, could be beneficial.

b) If the utility service imposes demand charges: In this case, the customer is charged a fee that varies depending on total electricity consumption amount. The fee might depend on how much electricity is purchased during peak hours when electricity demand is the highest. It may also be determined by the tot al amount of electricity you consumed monthly. In these cases, utilizing solar batteries may be beneficial, since the user may be able to avoid a higher fee by relying on his/her energy storage system instead.

c) If reduced or no net metering is imposed by the utility service: In case the sellback price of the utility service is lower than the electricity price purchased by the customer, it may be beneficial to install a battery in order to store the excess produced electricity and use during demand hour. This is because the price balance would be higher in case of power storage.

d) If power outage is to be prevented: In cases when the owner wants to prevent power outage, installing a solar battery could also be considered along with purchasing a fuel consuming generator. This approach may not only be more beneficial economically, but it also is a more environmental-friendly solution, since generators produce $CO_2$-contained exhaust gases. In case of carbon production reduction intentions, battery installation is worth looking into.

Regarding the battery size, it mostly depends on how many hours of house demand fulfillment is expected from the battery pack, which is called the battery autonomy. The depth of discharge is also an important factor, since the batteries should not be completely discharged during the cycle due to operational constraints. The battery voltage is al so determining, 24V mostly being proposed for household scenarios including consuming appliances like fridge, chillers, etc. The approximate required battery capacity is estimated by Eq. (5) in ampere-hour:

$$C_{bat} = \frac{E_{load}}{U_b} \cdot \frac{H}{DoD'}, \tag{5}$$

In which $\boldsymbol{C_{bat}}$, $\boldsymbol{E_{load}}$, $\boldsymbol{U_b}$, $\boldsymbol{H}$, and $\boldsymbol{DoD}$ represent the battery capacity in Ah, daily average load during the high-demand season of the year in W, battery bus voltage in V, battery autonomy in hours, and depth of discharge in percentage, respectively. Since in our case, the sellback price is approximately one-third of the grid purchased power, installing a battery of 500 Ah of approximate power is recommended. For calculating this capacity, two-third of daily electricity consumption is assumed to take place during evening and night, when there is no sun, and the battery is supply the required power for almost 7-8 hours of consumption in the absence of solar insolation. Also, a 0.8 depth of discharge is assumed for our case study. There is also a need for a charge controller device, leading the battery system to cost about 700 CHF on average.

Fig. 10 shows the state of charge of the installed battery. Also, Fig. 11 shows the purchased energy from grid as well as energy sold to grid. It is observed from the figure that much less energy is sold to grid during the day and most of the evening required energy is supplied by the battery. This is due to reduced net-metering tariff status.

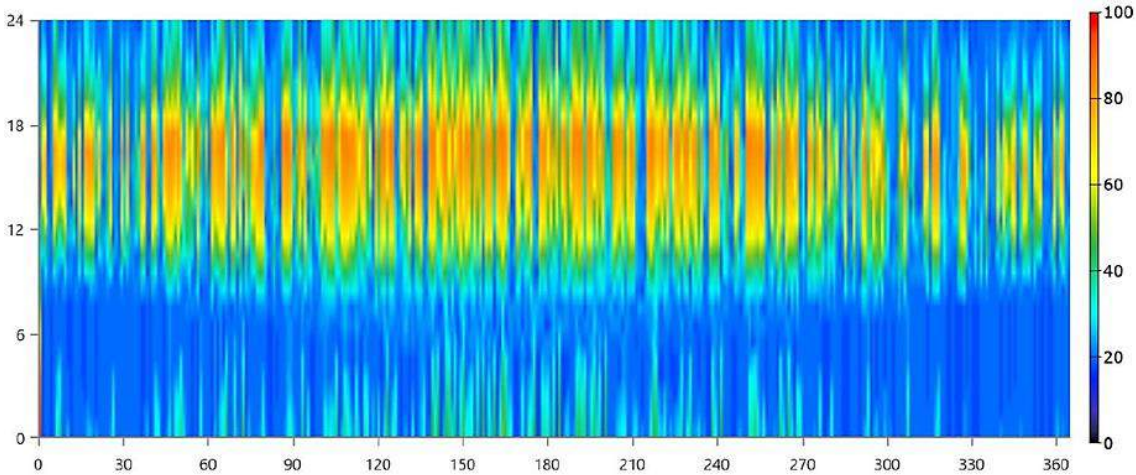


Fig. 10 State of the charge of the designed battery

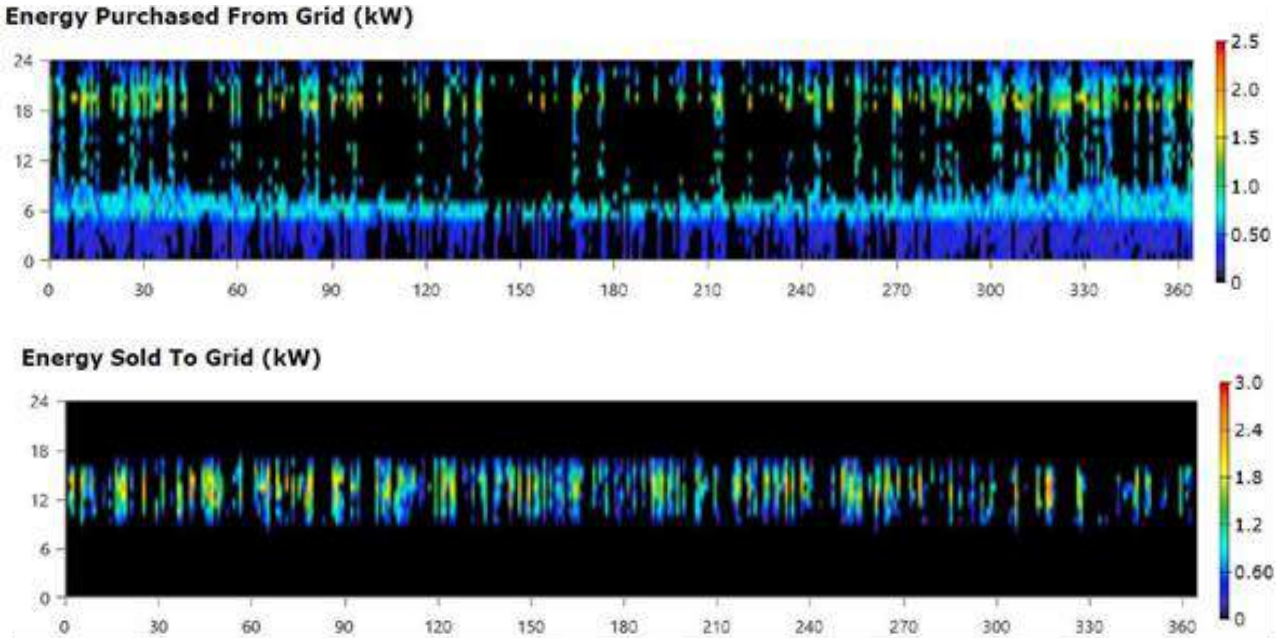



Fig. 11 Energy sold to and purchased from the grid during the daily hours throughout the year for the battery backup scenario

## 5. INSULATION SCENARIOS-PROCESS HEATING

Regarding the house insulation, three scenarios are considered: wall-only insulation, roof-only insulation, and wall and roof insulation. Each scenario resulted a payback period of 37, 157, and 50 years, respectively. For each case, an amount of 0.53, 0.1, and 0.63 kg $CO_2$ will be saved on an annual basis. The followings are therefore mentioned and recommended:

- The roof only scenario is absolutely obsolete due to drastically high payback period. If any insulation is aimed to happen, it is recommended that only the walls are insulated considering the building is already about 40 years of age. If carbon production fines are to be imposed, the payback period could be reduced and insulation is more justified. However, still the wall-only scenario is recommended.

### *5.1 PV system installation*

Regarding the PV system installation, a 4.8 kW system is designed for the house occupying approximately 30-35 $m^2$ of roof space (including the electrical equipment and maintenance spacing). Two scenarios of battery-less and battery backup cases are considered, which cost roughly about 10000 CHF and 11000 (considering the taxes and government incentives simultaneously) and have payback periods of 9 and 8 years, respectively. Furthermore, this system will save approximately 3.7 tons of $CO_2$ emission for a 30-year life span. The followings are therefore mentioned and recommended:

The decision depends strongly on the available local state incentives and tariff package. Although 8-9 years of payback period are quite high, they are still considered to be economical decisions to be made. Specially, if any carbon fines or higher grid electricity prices as well as higher sellback prices are predicted to take place in the system life span, which will decrease the payback period. Among the two scenarios, the battery backup scenario proves to be a little more economical and therefore recommended. This system also has the advantage of preventing the power outage of the house in evenings in case of grid outage and somehow eliminates the requirement of a generator. Further detailed design and economic analysis based on comprehensive local consumption trend and state incentives and tariffs are recommended.

*5.2 Heating design tools*

The use of Energy design tools can provide the confidence necessary to proceed with new ideas and thus move forward in improving building design and innovation. For this purpose, a comprehensive work was carried out involving the simulation of the conventional building case, which was assumed to be once in cold-weather climate conditions (Switzerland) and once in hot-weather climate conditions (Kuwait). The effectiveness of such insulation systems was investigated in these cases, where the internal temperature was taken about normal room temperature (20.8 ºC), and the outdoor air temperatures in Switzerland and Kuwait were considered to be (13 ºC) and (40 ºC), respectively.

When issues become more complex or critical it is likely that the use of higher-level simulation tools will become necessary. The Heating Design module (TiSoft) was used to obtain the overall energy requirement ($Q_N$) in both cases based on DIN4701 German Standard committee (Heating and Ventilation Technology). However, the main aim in the use of tools, in energy efficient design in general, is in achieving the optimum balance between all factors to minimize energy consumption. Unfortunately, no design tool can do this automatically. It is an iterative process involving the expertise of the design team itself, together with appropriate design tools. The geometry of the building will play an important part in any analysis of its energy performance. Many simpler tools only accept vertical wall and window elements, horizontal floors and flat, sloping or pitched roofs. However, as the sophistication of the tool increases, the complexity detail of the geometric model accepted by the tool generally increases also. Fig. 12 represents the geometry of the building examined in this study. Perhaps the most important element of building geometrical data input relating to energy analysis is the building material description. More developed tools will provide built in databases of the properties of typical materials as individual components, or as typical constructional elements such as walls, windows, etc. All of these issues are inter-related, in that they can directly or indirectly affect one another and the overall energy performance of a building or services system.

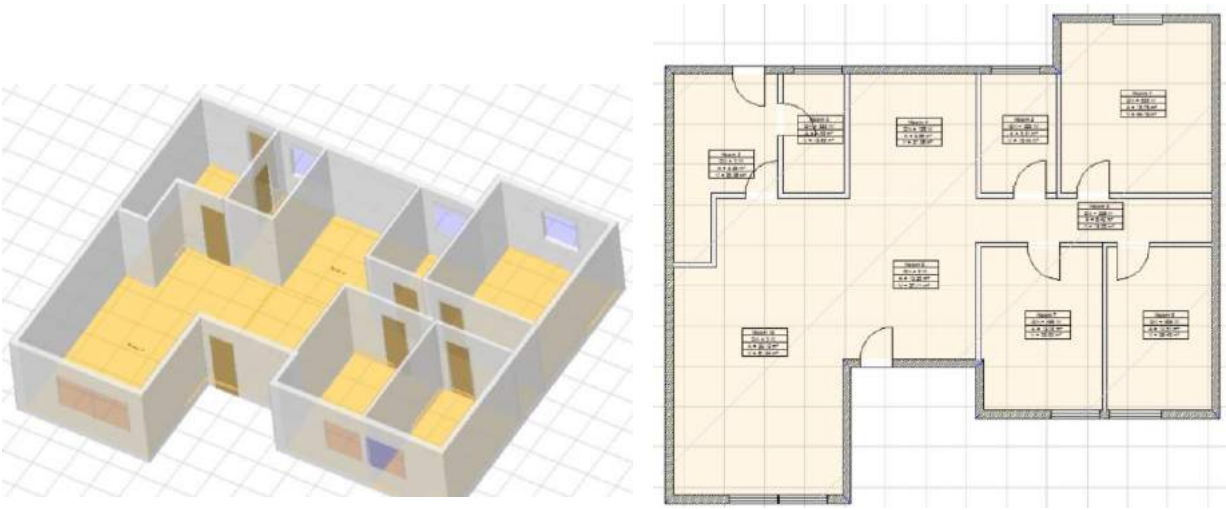


Fig. 12 The geometry of the building (3D model) designed by Energy-design tool (TiSoft)

The results obtained by Energy-design software are shown in Table. 8. It was demonstrated that implementation of the correct type of insulation in these cases, can substantially reduce the houses use up to 65% (under 100 kWh/m$^2$). However, the effectiveness of such insulation systems would decrease when applied to structures in a hot climate such as that of Kuwait, reduce the houses energy use up to 33%.

Table .8 The overall energy requirement of the building for both cases

| Location of the building | Temperature (ºC) | Building Conditions | The overall energy requirement $Q_N$ (w) (DIN 4701 Standard) | Total Energy Saving (%) |
|---|---|---|---|---|
| **Switzerland** | Internal: 20.8 | Without Insolation | 4855 | **65%** |
| | Outdoor: 13 | With (15cm) Glass-wool Insolation in Exterior-walls | 1700 | |
| **Kuwait** | Internal: 20.8 | Without Insolation | -5759 | **33%** |
| | Outdoor: 40 | With (5cm) Glass-wool Insolation in Exterior-walls | -3857 | |

## 6. Evaluation of a new insulation technique to prevent mold growth in thermal bridges

Mold growth and moisture problems in buildings represents a widespread issue. Most of the existing residential buildings are poorly insulated and heavily affected by the presence of thermal bridges, that constitute the first area colonized by mold. In this part, a non-insulated residential masonry building located in Switzerland considered as a real case-study, which was affected by indoor mold exposure. The first mold symptoms were detected in summer-time, wherein the intersection between the inner wall surface and the non-insulated horizontal slab in the living room represents a particularly critical area of mold growth, as shown in Fig.13. For the identification and characterization of the structural defects, infrared thermography procedures were used in this work (Fig.14), where outer heating source utilized for creating temperature difference between the damaged and non-damaged areas. Thermal imaging as a nondestructive, real-time and non-contact technique can be used for small surface analysis. The relative humidity measurements were also carried out by Hygrometer device (Fig.15) for the initial evaluation of the assessment parameters. The short-term measurements do not comply with the requirements of SIA Standard 180: 2014.

Fig.13 The critical area of indoor mold exposure, a residential masonry building located in Switzerland

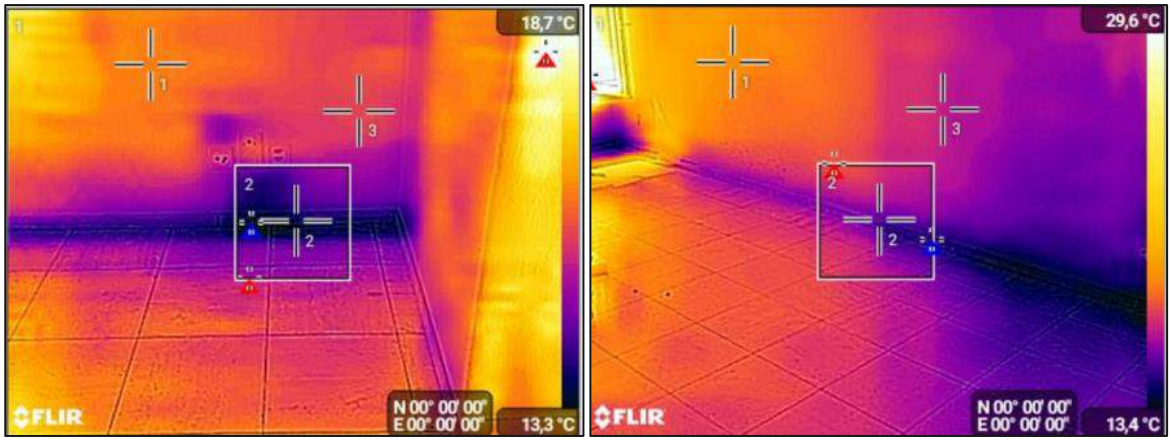



Fig .14 The thermal imaging of indoor walls, a residential masonry building located in Switzerland

Controlling excess moisture is the key to preventing and stopping indoor mold growth. Identify and fix the moisture problem, after removing the mold contaminated material and cleaning the surfaces, is essential for this purpose. Careful analysis and reasoned selection of insulation system should be based on initial cost estimation, effectiveness of insulation system, and more comfortable living conditions, wherein the walls will remain breathable. But it is not possible to achieve comfortable living conditions if the building itself does not have good thermal insulations. To create both horizontal and vertical barriers against lateral moisture penetration in masonry walls, "HP-K Pro" as a new insulation material was selected and injected into the 14-mm diameter holes at spacing of 25cm from face of the identified problem areas of the walls (Fig.15). HP-K Pro is special polymer incorporated into a low-viscosity, high-purity paraffin oil, where it spread and formed a perfect water barrier in the walls. The relationship between the amount of heat transfer with the outdoor temperature and relative humidity through masonry wall were numerically calculated using the finite element software COMSOL Multiphysics, and the model was validated on the basis of experimental measurements in summer. In order to study the heat and moisture transfer in building exterior walls and effectiveness of such moisture-barrier insulation during cold seasons, two models were assessed by the COMSOL Multiphysics solver, before and after implementation of moisture-barrier insulation. This software solves coupled heat and moisture transport equations by finite-element formulations where the temperature and relative humidity are the driving potential for the heat and moisture transport through the material.

Fig.15 Injection 'HP-K Pro'-Paraffin oil through indoor walls, and Hygrometer device

### *6.1. Coupled Heat and Moisture Trasfer Through the Building Material*

The hygrothermal analysis of porous material is complex because heat and moisture transfer are transient and highly coupled with each other. Even though experimental studies are the most direct approach for studying the moisture performance of building envelopes, testing is very costly and time-consuming. In particular, very long experimental durations would be necessary due to very low speed of moisture migration. Therefore, it would be difficult to experimentally investigate varieties of building assemblies under different kinds of indoor and outdoor conditions. On the other hand, numerical simulation techniques can provide relatively fast estimates of the heat and moisture performance of the building materials with acceptable accuracy. The theory of heat-moisture coupling transfer model established by researchers is based on the principle of energy conservation, mass conservation, Fourier's law, Fick's law and Darcy's law. According to these laws, many models have been established by the predecessors. Previous studies highlighted the importance of a detailed hygrothermal analysis (i. e. the temperature and the relative humidity distributions, the water vapor, and heat flows) to predict correctly both the energy consumption and the risk of mold growth and building material degradation caused by the excess of indoor humidity. For Moisture transport, two potentials are necessary: the vapor pressure for diffusion and the relative humidity (derived from the capillary pressure) for liquid transport. Since the vapor pressure is a function of temperature and relative humidity the coupled transport equations can be written as follows (EN 15026) [12]:

- $$\frac{dH}{dT}\frac{\partial T}{\partial t} + \nabla q = Q \quad , \quad \begin{cases} q = -[k_{eff}\nabla T + L_v \delta_p \nabla(\emptyset p_{Sat})] \\ \frac{dH}{dT} = (\rho C_p)_{eff} = \rho_s C_{\rho,s} + w C_{\rho,w} \end{cases}$$

- $$\frac{dw}{d\emptyset}\frac{\partial \emptyset}{\partial t} + \nabla g = G \quad , \quad \begin{cases} g = -\left[\xi D_w \nabla \emptyset + \delta_p \nabla(\emptyset p_{Sat})\right] \\ \xi = \frac{dw}{d\phi} \end{cases}$$

$\therefore$ *Coupling Equations for Heat and Moisture Transport*:

$$\begin{cases} \left(\rho_s C_{\rho,s} + w C_{\rho,w}\right)\frac{\partial T}{\partial t} + \nabla.\left[-k_{eff}\nabla T - L_v \delta_p \nabla(\emptyset p_{Sat})\right] = Q \\ \xi \frac{\partial \emptyset}{\partial t} + \nabla.\left[-\xi D_w \nabla \emptyset - \delta_p \nabla(\emptyset p_{Sat})\right] = G \end{cases}$$

- $\frac{dH}{dT}$ *or* $(\rho C_p)_{eff}$ : The effective volumetric heat capacity at constant pressure ($J/(m^3 \cdot K)$)
- $k_{eff}$: The effective thermal conductivity associated with the moisture content ($W/(m \cdot K)$)
- $L_V$: The latent heat of evaporation (J/kg)
- $\delta_p$: The vapor permeability of material (s)
- $\phi$: The relative humidity (dimensionless)
- $T$: The tempeture (K)
- $p_{sat}$: The vapor saturation pressure (Pa)
- $Q$: The heat source ($W/m^3$)
- ξ: The moisture storage capacity ($kg/m^3$)

• $D_w$: The moisture diffusivity ($m^2/s$)

• $G$: The moisture source ($W/m^3$)

The developed numerical model is implemented in the commercial simulation software COMSOL Multiphysics, which is based on the finite element method and an explicit scheme with variable time stepping. Constant material properties and values can be entered as parameters, and variable coefficients can be defined either as analytical functions or as a list of discrete values generating interpolated functions. Heat and moisture equation are solved simultaneously with COMSOL's built-in time-dependent solver.

In order to study the relationship between the amount of moisture transfer with the outdoor temperature and humidity through the (0.2 m) masonry wall, three research contents will be set. The outdoor temperatures and humidity are set as different boundary values in turn, and the solver's time step size of the software is set to 1 day. The moisture transfer differential equations system is solved by the COMSOL solver. The three research contents are: • Study-A: (Summer-Without moisture insulation) The outside air temperature, inside temperature are 302.5 K and 290K, respectively. The temperature intersection between wall and horizontal slab is 298K, and the initial outside relative humidity is 0.42. • Study-B: (Winter-Without moisture insulation) The outside air temperature, inside temperature are 282 K and 283.5K, respectively. The temperature intersection between wall and horizontal slab is 281.5K, and the initial outside relative humidity is 0.79. • Study-C: (Winter-With moisture insulation) The outside air temperature, inside temperature are 282 K and 290.5K, respectively. The temperature intersection between wall and horizontal slab is 281.5K, and the initial outside relative humidity is 0.47.

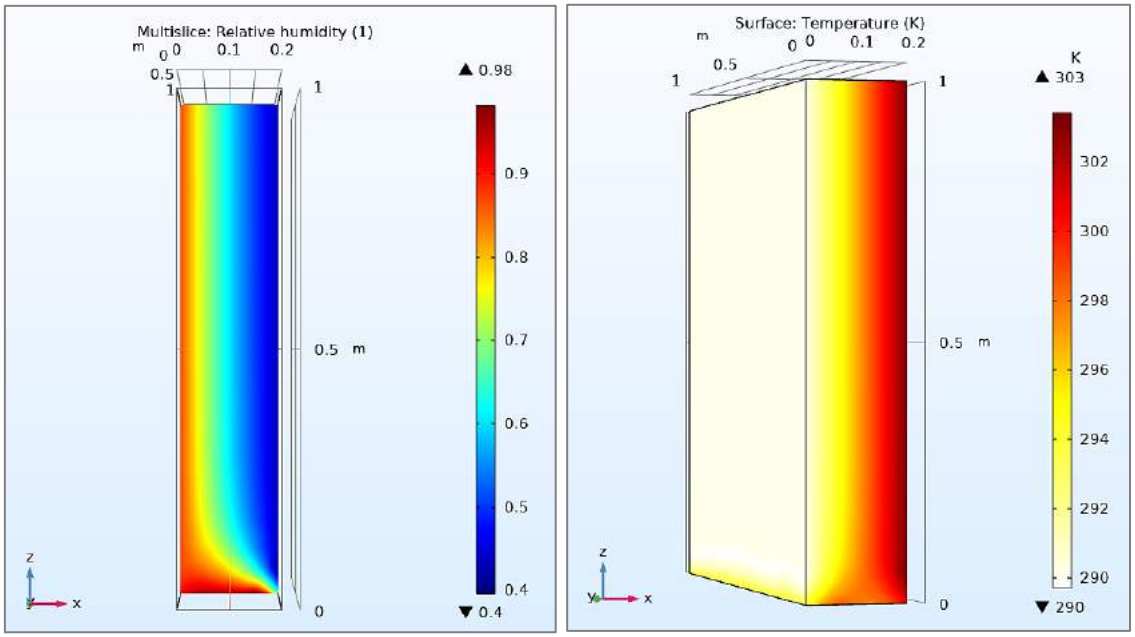



Fig.16 Study 1: Coupled Heat and Moisture Transfer Through the 0.2m masonry wall COMSOL simulation results for (Summer-Without moisture insulation-Experimental Case)

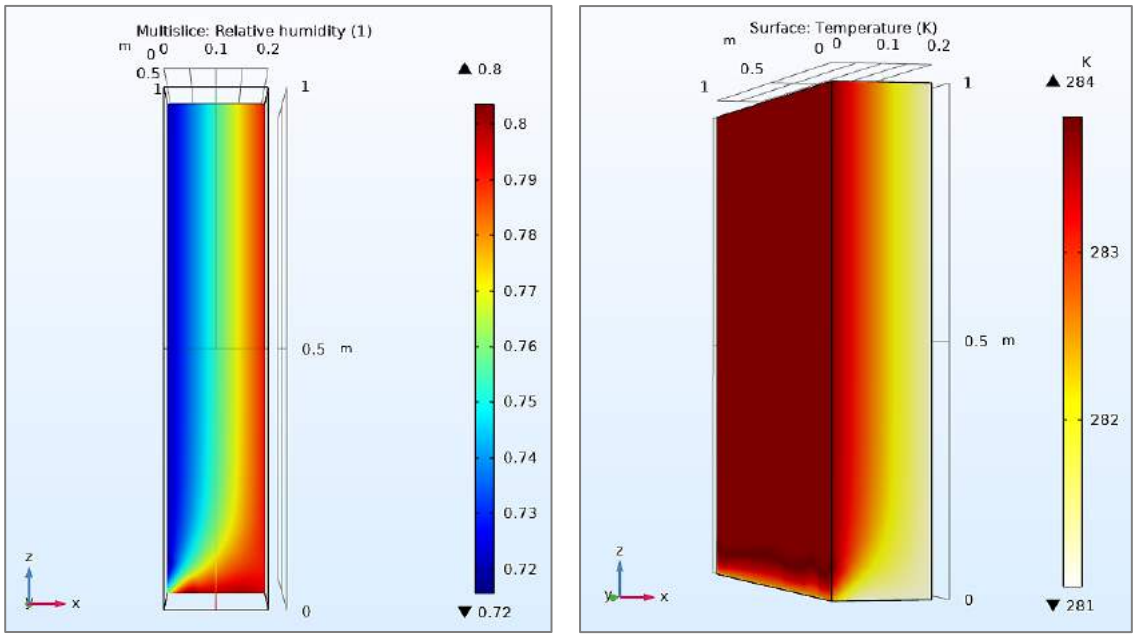



Fig. 17 Study 2: Coupled Heat and Moisture Transfer Through the 0.2m masonry wall COMSOL simulation results for (Winter-Without moisture insulation)

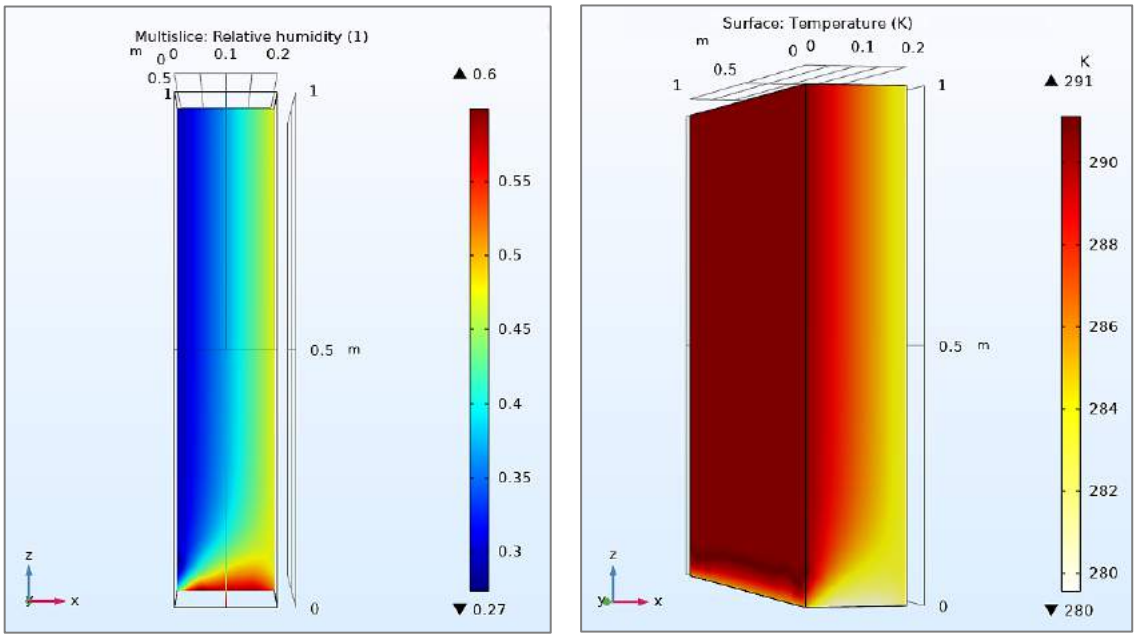



Fig. 18 Study 3: Coupled Heat and Moisture Transfer Through the 0.2m masonry wall COMSOL simulation results for (Winter-With moisture insulation)

The conduction of heat causes evaporation or condensation of water. Similarly, the moisture also causes changes by latent heat when the phase change occurs. As shown in Fig.16, due to the existence of water vapor concentration gradient and gas pressure gradient, the flow of water vapor occurs inside the porous medium; the capillary medium has a capillary pressure gradient due to the difference in water content. The water inside the porous medium flows under the action of the capillary pressure gradient and the gas pressure gradient. The flow of water vapor and the flow of liquid water are also accompanied by the transfer of heat. This model was validated on the basis of experimental measurements, thermal imaging contents and moisture measurements. It can be concluded from the obtained

results of study-B and study-C that the injection of HP-K Pro-Paraffin as a moisture barrier material establishes the following interior side conditions:

The repeated experimental measurements a month after implementation of the new insulation system revealed a significant decrease (~about 50%) in humidity content, and a trend toward increased the wall surface temperature in cold weather. It seems that moisture-barrier insulation system prevents liquid or capillary flow across it, and the inside moisture content is reduced by more than half; thus, according to the DIN (German Code) prevents moisture and temperature conditions favorable to mold growth (as shown in Fig.19). Besides, a decrease in energy consumption can be attained up to 20% by implementation of moisture-barrier insulation. The importance of the moisture-resistance insulation is due to the need to reduce energy consumption and the desire to improve comfort. Accordingly, properly injection of HP-K Pro leads to well-sealed and well-insulated house, as well as lower initial expense and operating costs compared with the other conventional insulation materials. Therefore, if it can be used in porous material such as masonry walls, make good insulation system.

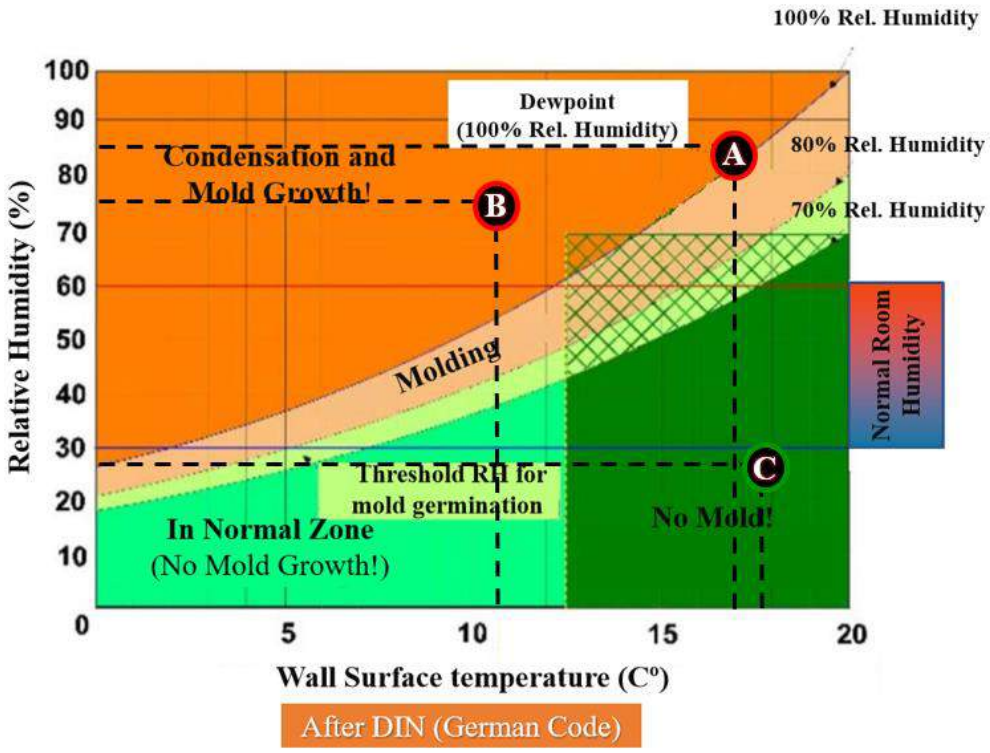



Fig.19 DIN (German Code) - Probability of MOLD formation [13]
(A) Summer-Without Moisture Insulation (Molding Problem)
(B) Winter-Without Moisture Insulation (Molding Problem)
(C) Winter-With Moisture Insulation (No mold)

## 7. ENERGY CONSUMPTION SIMULATION BY USING HAP SOFTWARE, KUWAIT

### *7.1. Methodology*

Modeling energy consumption was carried out using Hourly Analysis Program 4.7 (HAP) energy simulation software, and optimizing the results will done MATLAB. The optimization parameters include those of building envelopes, windows, fenestration, and

HVAC parameters (i.e. overall heat transfer coefficients, windows SHGC, and unit cost). Two base cases are; Case 1 involved commercial building and Case 2 involved residential building. A multi-objective function with inequality constraints, constrains are: parameters values < +20% of Kuwait code value and parameters values > –20% of Kuwait code value with an increment of 2.5%. The data was optimized with the payback calculations as a necessary optimality condition [14-21].

### *7.2. Discussion*

Payback period (PBP) analysis was applied as an optimality condition. The consumer benefit is less than five years. Optimization process for the large data was conducted. Using the data of Table. 9, the $CO_2$ emissions were reduced by 10% approximately for base Case 1. In base Case 2, the $CO_2$ emission has a reduction percentage of 7% was applied by the optimized values of the assessed parameters (see Table.10). The reduction of the optimal solution in the $CO_2$ emission of base Case 1 was higher than base Case 2. This is due the lower values of the SHGC and U-Window.

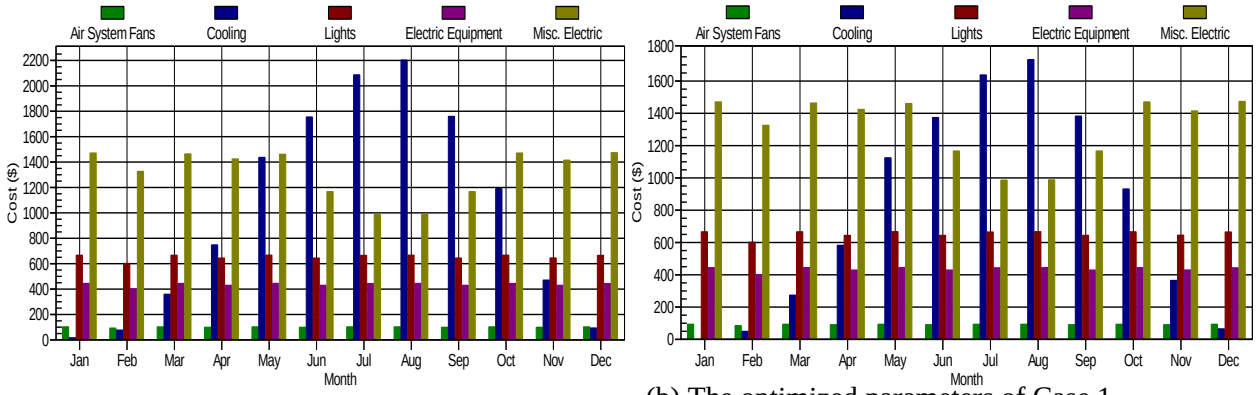
Table. 9 The optimized parameter values of base Case 1 and their effect on the annual energy consumption plus its payback periods.

| Parameter | Optimized Value | Parameter Percentage (According to the Kuwait Code) | Reduction Percentages on AEC | Payback Periods (Year) |
|---|---|---|---|---|
| U-Wall | 0.08 | –20% | 0.534% | 1.8 |
| U-Roof | 0.056 | –20% | 0.420% | 1.1 |
| U-Window | 0.557 | –5% | 0.124% | 4.8 |
| SHGC | 0.237 | –17.5% | 0.984% | 4.8 |

Table. 10 The optimized parameter values of base Case 2 and their effect on the annual energy consumption plus its payback periods.

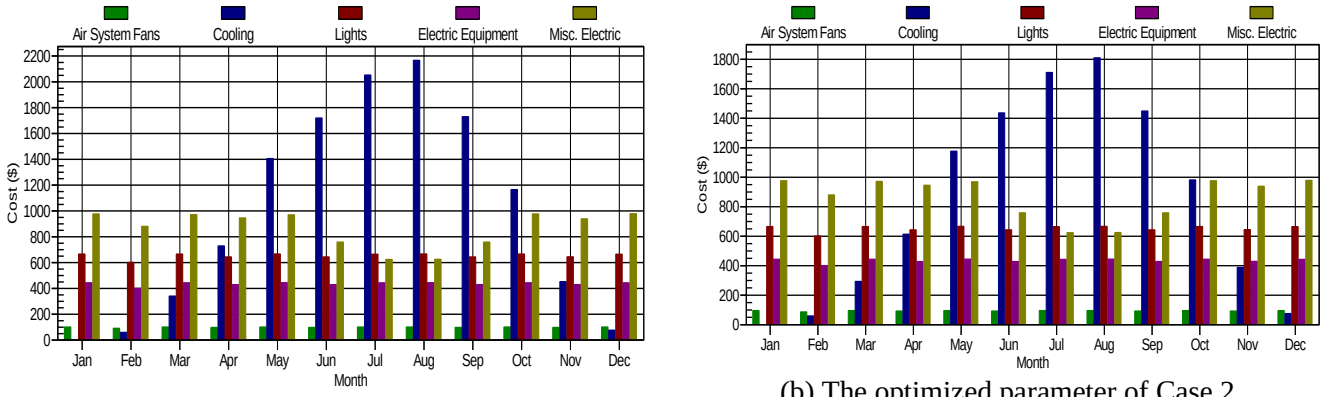
| Parameter | Optimized Value | Parameter Percentage (According to the Kuwait Code) | Reduction Percentages on AEC | Payback Periods (Year) |
|---|---|---|---|---|
| U-Wall | 0.08 | –20% | 0.605% | 1.9 |
| U-Roof | 0.056 | –20% | 0.476% | 1.1 |
| U-Window | 0.572 | –2.5% | 0.0514% | 2.7 |
| SHGC | 0.244 | –15% | 0.965% | 4.5 |

*AEC: Annual Energy Consumption (KWh).




(a) Case 1 (b) The optimized parameters of Case 1

Fig. 20 Monthly Peak Load by end use in ($) for base Case 1 using Kuwait Code parameters and using the optimized parameters values of base Case 1




(a) Case 2 (b) The optimized parameter of Case 2

Fig. 21 Monthly Peak Load by end use in ($) for base Case 2 using Kuwait Code parameters and using the optimized parameters values of base Case 2.

- In base Case 1, the increase in occupancy and plug loads fluctuations increases the total energy consumption and $CO_2$ emissions by at-most 13% over Case 2. This influences the increase in environmental pollution and harmful effects on human health. Energy consumption is anticipated to increase by increasing the occupancy and the plug load.
- Lower energy consumption and $CO_2$ emissions can be achieved by proper choice of glass which delivers a positive impact for the environment in energy savings. Through analyzing the U-Window and SHGC parameters, was found to be more effective is reducing the SHGC of the fenestration system of the residential and commercial buildings, which was critical to performance less energy consumption. A lower SHGC value is advantageous in cooling load consumption.
- The U-Window parameter was the most effective value on the incremental initial cost.
- For base Case 1, a reduction of 6.1% in the annual energy consumption was obtained with the optimized values of the assessed parameters. Furthermore, a potential to save up to 5.3% of cooling energy in optimized values of the assessed parameters of base Case 2. The optimized values of the assessed parameters covered the annual costs within less than five years in comparison to Kuwait Code.

- An energy cost savings of 20.8% in the peak load was obtained using the optimized assessed parameters values for Case 1. In addition, it was an approximately of 15.5% and 15.1% due to July and August respectively, for Case 2.

## 8. CONCLUSIONS

The energy in building sectors is responsible for about 40% of final energy consumption and more than 55% of global electricity demand in developed countries, which have gained considerable attention during recent decades. Energy efficient building design as a multidisciplinary field of research encompasses several areas of study including Civil engineering, Electrical engineering, as well as economics and decision-making processes.

- The most sustainable energy design technique is to conserve energy as much as possible. There are various methods to reduce the use of conventional energy from fossil fuels to meet the energy requirement for the building. The combination of various solar passive design aspects can easily be integrated in new buildings based on the site, orientation of building and local climatic conditions.

- Careful analysis and reasoned selection of insulation system should be based on initial costs estimation, climate, personal preferences, available budget, and effectiveness of insulation system for more comfortable living conditions. A well-insulated building, whether commercial or residential, is both an energy-efficient and cost-efficient choice because it reduces the cost incurred by a heating or cooling system. Besides, it is difficult to provide enough warm air to increase the surface temperature of the wet walls, and it takes more energy and higher heating costs to warm up moist air. It was demonstrated that properly injection of HP-K Pro as a low-viscosity, high-purity paraffin oil leads to well-sealed and well-insulated house, as well as lower initial expense and operating costs compared with the other conventional insulation materials, prevention of mold growth conditions, and healthier indoor air quality. Therefore, if it can be used in porous material such as masonry walls, make good insulation system.

- Solar Energy Systems can be applied in a very harmonic way on buildings to cover the heating, cooling, electricity and lighting needs. This reduces the need to consume energy from other sources and provides a comfortable environment inside.

- The economic justification of including a battery in the system strongly depends on the tariff plans and power outage prevention sensitivity. In cases of time-of use tariff plans, demand charges, and reduced or no net-metering, batteries could be absolutely economic, although they extend the capital costs mostly due to replacement requirement every 3-5 years. They could also be considered as a greener and possibly more economical alternative to fuel consuming generators used for preventing house power outage.

- Due to a reliable grid connection, installing an off-grid system for covering all household demand is absolutely not recommended. This is mostly because such system requires a lot of space and a huge and costly battery room, overly extending the capital cost and making it not justified. However, if the system is just to provide a portion of the demand off-grid, it could be justified, but requires deep investigation. It is worth mentioning again that the PV system should be installed by a credible experienced technician team, since not only the system is meant to operate for long

periods of time, installations by inexperienced personnel could impose serious threats to the house and the residents.

This study can lead to a better insight into the sustainable energy design in different climate situations, and could be used as a benchmark study for future investigations.

## ❖ Future works:

The following items are proposed for future study and investigation:

 Provided that thorough and comprehensive data of consumption patterns, house appliance list along with technical specs, and tariff and incentive plans are supplied, the team is capable of conducting a full detailed design for the PV power system. The detailed design will include synchronized component selection, step-by-step action plan manual, and a detailed economic analysis. Multiple brand selection scenarios could also be considered based on economic preference.

 In case of requiring a battery-backup system, the system with battery backup could be designed and economically analyzed. The acquired results could be compared with the battery-less grid-connected scenario.

 In case adequate input data are provided, the heating and cooling loads of the house could be thoroughly simulated and analyzed in HOMER PRO as well as other related engineering software. The simulation results could be useful for further planning the insulation measures.

 Other renewable energy scenarios could also be considered and analyzed for the house, including the geothermal systems and biomass utilization. The economic justification of each system could be thoroughly analyzed and compared with the PV system scenario.

**ACKNOWLEDGMENTS**

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