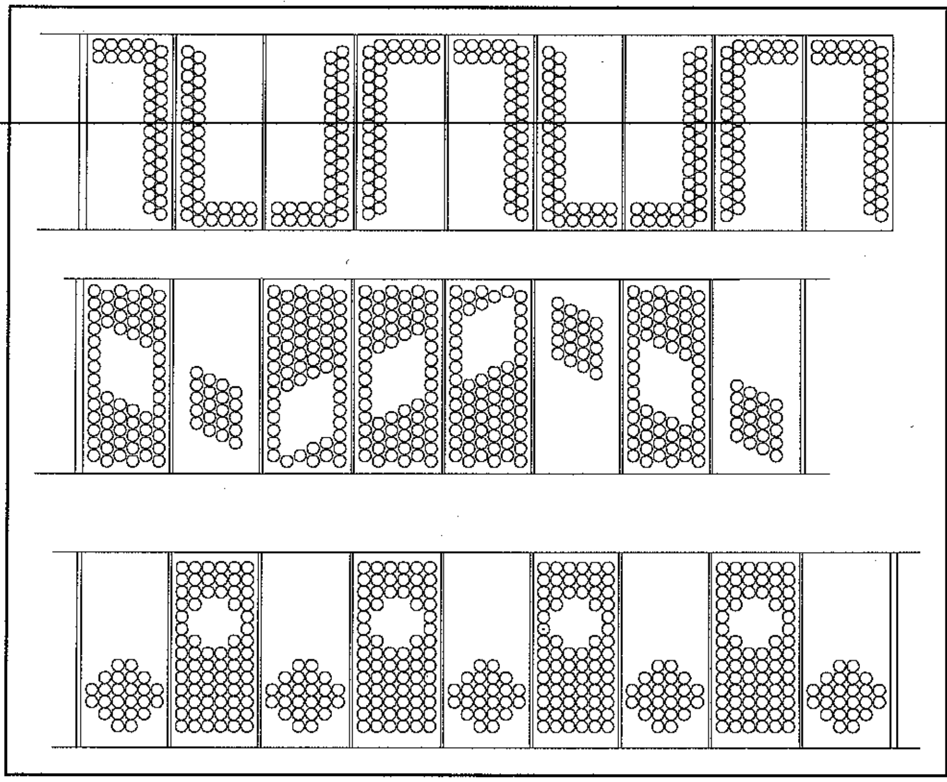
INTEGRATION OF SOLAR CELLS IN THE WINDOWS OF SKIBSTEDFJORD TRAINING CENTER



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1 Introduction

This report will give an overview over problems that have to be considered when designing a photovoltaic plant for grid connection. The idea of this particular plant is not only to demonstrate the environmentally friendly use of the renewable energy of the sun, but also to show an example for a special integration of solar cells into the facade of a building. The costs of building a pv- power plant are relatively high considering the price for material and installation compared to the production of energy. But the pv-generator can also be integrated into roofs and facades replacing very expensive materials like marble or granite. In a way it could be a kind of fashion or let us say culture to use eco-friendly (and expensive) solar cells instead of only expensive marble. Now here instead of using common photovoltaik modules the cells will be put in between the two layers of glass of the window. The window integration will save the costs and the material for the module production by using a glass-window-facade which has to be built anyway. The window area covered by the cells will not let light inside the room, but will still produce heat due to the fact, that only 14% of the sunlight will be converted to electricity. The design will not only save the module costs but also the frame, where modules usually are placed. Realizing this window converted function it is easy to comprehend that there will always be disagreements between technical and, let us say, architectural points of view. The building concerned is the new training center, Skibsted Fjord, with its slightly leaned back window front. The different rooms will be used as restaurant, conference hall and seminar rooms with varying needs of light and view as well as offering different front angles to south. Following, the very often hard to combine aspects of technique, technology, art and architecture will be discussed whereas taste cannot be discussed about. Finally some remarks about the connection to the grid and the inverter will be made.

2 Aspects of Design

2.1 Architectural Point of View

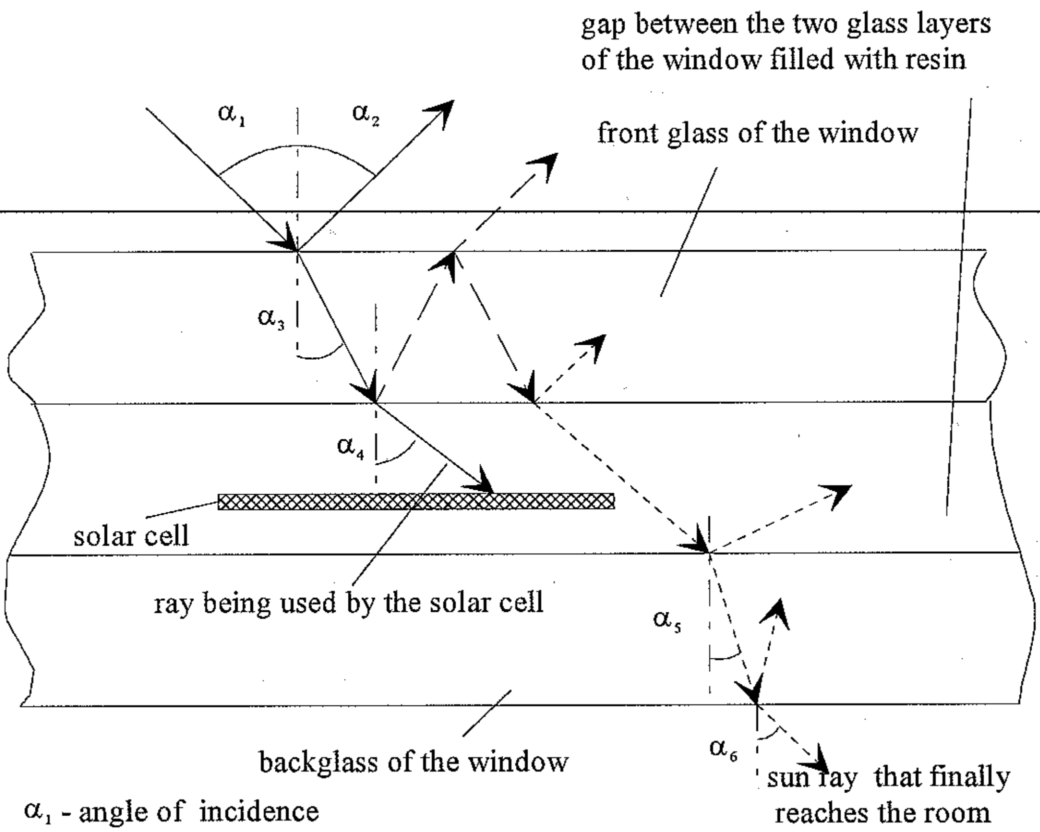
First of all let me remind on the purpose of windows in general, to let light inside. Therefore it seems to be unwise to fully cover a window area with solar cells. An exception could only be made for additional windows that are not really being needed for more light or that are blocked by posts anyway as in this case sometimes. So it is very important to find the right or best suitable windows. Another not to be neglected point is the change of view that will follow if either the lower or the upper part of the window will be covered. For a conference hall it is probably not so important to get an interesting picture looking out, but for a restaurant it might be as deciding as the meals presented. Again this is always dependent on people's taste and opinions. Some of them might prefer to look at the sky while eating, others will rather observe the playing light impressions of the sun on the earth wandering further. Certain pattern of cells will also give another feeling of harmonic order to different people depending again on taste as well as physical dimensions. A tall person can easily look out of a high window, while a smaller might not even reach it. Here comes another point to be thought on, the position and height of the window. A very tall window could look elegant for one person, but useless in terms of light and view to another. Following that some will prefer to put the solar cells in the upper part, maybe working as sun protection additionally, others prefer them in the lower part, because they rather have the sky then the ground to look at.

Thinking on an office in a hectic city most people probably would go for shunning out the trouble outside.
All in all this aspect is so much varying with personal taste and opinion, that it seems to be impossible to find a general agreeable solution. A decision will have to be made considering the technical necessities.

2.2 Technical / Technological Aspect

The technical possibilities often cut the art designs having been made. First of all the solar cells have to be connected. Practically the output and input should be at the same side of the window, which means that only an even amount of cell rows will be aloud. Furthermore it would be unwise to have a connection between two cells drawn over the whole window. They have to be kept as short as possible considering losses and also the look of it. Not to be neglected is the possibility of using bypass diodes for parts of the cell pattern in case of part shade. That would demand certain connection junctions within the pattern. On the other hand it might not be worth using bypass diodes for less than a whole window, e.g. depending on the number of cells. Considering the whole system a minimum amount of solar cells has to be used according to the power output desired. This and the pattern that will be used give an idea about how many windows will be needed.
Let me here just remind on the fact that window fronts with different angles to south cannot be connected to the same system. Due to another radiation angle the current would be different in the cells of these fronts. Now since the cells and the windows are connected in series the cells with the lower current will predict the maximum possible current in the whole system. Therefore the cells of the front with the higher radiation cannot be used effectively.
To be considered are also any windows shadowed that might occur during the daily path of the sun, because cells would be useless there. So certain windows beside entrances will not be used. Due to the same effect there will be a spare distance between the frame of the window and the first row of solar cells.
Now for the installation of the cable channel there are two ways of placing it, either on the ground or above the window under the ceiling. For the electrician installing the system it will certainly be easier to work on the ground instead of getting up a ladder and working over head. Unfortunately the area exactly behind the window in the restaurant part will be used as a small greenhouse or at least will have plants that need to be watered regularly. Here it would be very likely, that someone repeatedly steps on the cable channel or even waters it. Therefore it should be preferred to have it out of reach above the window.
At last there shall be some words about the technology of this system. When sun rays hit the surface of glass some will always be reflected others refracted depending on the material (fig.1). Now on the backside of the front glass layer the same process happens again. Considering these two boundary layers the sun rays that finally reach the solar cells have been reduced already twice. That means that only a part of the incoming sun rays can be used by the solar cells to produce electricity. Therefore common solar panels are made using special glass for the front glass. Depending on the company and the type it would be a special hard glass with a low iron content to reduce reflection. A high temperature would extremely reduce the efficiency of the cells. Therefore there would be a back covered with e.g. aluminum foil. Now in this case the backside in the window cannot be covered with any material. That will cause a higher temperature in the window demanding a special care for the material used between the glass layers. In solar modules one will find resin or EVA-plastic. The technology for the solar cell integrated windows is thus that the solar cells will be fixed to one layer of glass, this will be glued onto the second on the rim of the layers leaving a small opening. Through this opening the gap will be filled with a special transparent material

that will harden after some time. Now this material has to be chosen concerning the temperature in the window and cooling possibilities. Also the front glass should not be a common glass used for windows but a special glass with low reflection, as mentioned above, but the back glass could posses especially high reflection. To use this reflection on the backside glass solar cells absorbing light from both sides could be used, though this might only make a small contribution to the energy production. From the point of view, that the pv-plant should produce as much energy as possible, the greenhouse should be cooled (as much as possible without using energy and not only in summertime !) or at least the window should be ventilated to keep its temperature down. That seems, of course, a contradiction to the purpose of a green house, but ventilation should be seriously thought on.



α_1 - angle of incidence
α_2 - angle of reflection on glass surface
α_3 - angle of refraction on the boundary air/glass
α_4 - angle of refraction on the boundary frontglass/plastic
α_5 - angle of refraction on the boundary plastic/backglass
α_6 - angle of exit glass/air

Fig. 1 Cross Section of Window

2.3 Conclusions for the Integration of Solar Cells in the Window front

Having considered all the points mentioned above several suggestions were made (see App.). App.1 shows a cross section and App. 2 the front view of the whole building. The right wing of the building stretching out eastways will inhabit the restaurant area. There is a long row of 13 windows that can be used regularly with the exception of the window right of the entrance due to shade. The first two windows on the other side of the row belong to the kitchen and therefore were thought to be covered more intensely with solar cells, only letting enough light inside for the kitchen work. For this front three different proposals (App.3, fig.1-3) have been made, from which fig. 2 and 3 will be favored. The windows left of this entrance and the whole next front of the conference hall cannot be used at all because of shade and pointing to the east. The next section being used belongs to the conference hall. Due to different angles the fronts have to be used separately. The door front cannot be used at all, because of shade being made by the portal, leaving the two side fronts with eight and nine windows. Now therefore two smaller inverters will be needed. Here the antagonism of using the windows effectively, especially with such a small number, and still letting enough light inside as well as enough view outside is very obvious. Out of the proposals fig. 4 - 9, App. 4 for these two fronts fig. 7 to 9 are favorites from which fig. 8 with 320 cells will give the maximum energy yield. The western section has again a long row of 14 windows and is going to offer seminar rooms. In this case another conflict came up. A higher number of windows easily provides enough solar cells, but how to place them. One could either choose a regular pattern using every window, but with less cells (fig. 11, 13) or could take a pattern with more cells per window forming groups of windows, but leaving spare windows in-between for a free look outside (fig.10, 12). Finally fig.13 was decided for.

3 The Connection to the Grid

3.1 The Public Utility

Once it was decided to feed the electricity produced by a photovoltaic plant into the grid the public utility becomes a partner. So far no international standards (IEC norms) have been agreed upon, neither Danish nor German (DIN/VDE) standards exist. To secure the interests of German utilities the German organization of public utilities (VDEW) published the "Provisional Guidelines for the Parallel Operation of Photovoltaic Plants and Low Voltage Grid" (/3/). Beside other things the points of main interest are

- Protection against feedback while voltage drop or rise in the grid (e.g. in order to work on a voltage free grid)
- Limitation for electromagnetic compatibility, harmonics, voltage distortion, etc.
- Power counting.

Now before one can connect a photovoltaic plant to the grid, one has to give a notification to the public utility, that has to agree upon the papers included in the notification:

- Position of plant
- Electric diagram
- Description of protection system (earth connection, lightning or differential voltage protection)
- Description of inverter and its connection to the grid as well as prove for certain demands (switching ability, harmonics)

For the public utility it is also of no little concern, whether the system is going to be able to perform island operation, because in this case an additional switch between connection point to the utility and distribution to the load including the PV-plant will always have to be accessible for the public utility (s.fig.2 next page). The switching devices have to be able to switch off the load, certainly, as well as the maximum possible short circuit current at the particular place. The latter depends on the plant, but also on the grid. Using melting fuses the switching ability has to be planned according to the time behavior of the fuse.

3.2 Block diagram

The block diagram of a photovoltaic plant can be seen in fig.3. The solar panels, in this case the windows, can be connected in series. A diode for each window will provide a current flow even if one window was shadowed and a diode in the plus phase protects the cells against a backcurrent.

It is very unlikely, that a lightning will strike the building, because it is mainly built into the ground and there are a lot of windturbines in that area. Never-the-less it is possible, that overvoltages might be induced in the system. Therefore two surge diverters should be installed, one for plus pole and one for minus pole, and be connected to an earthconnection as well as to all metal frames and metal cable mantles.

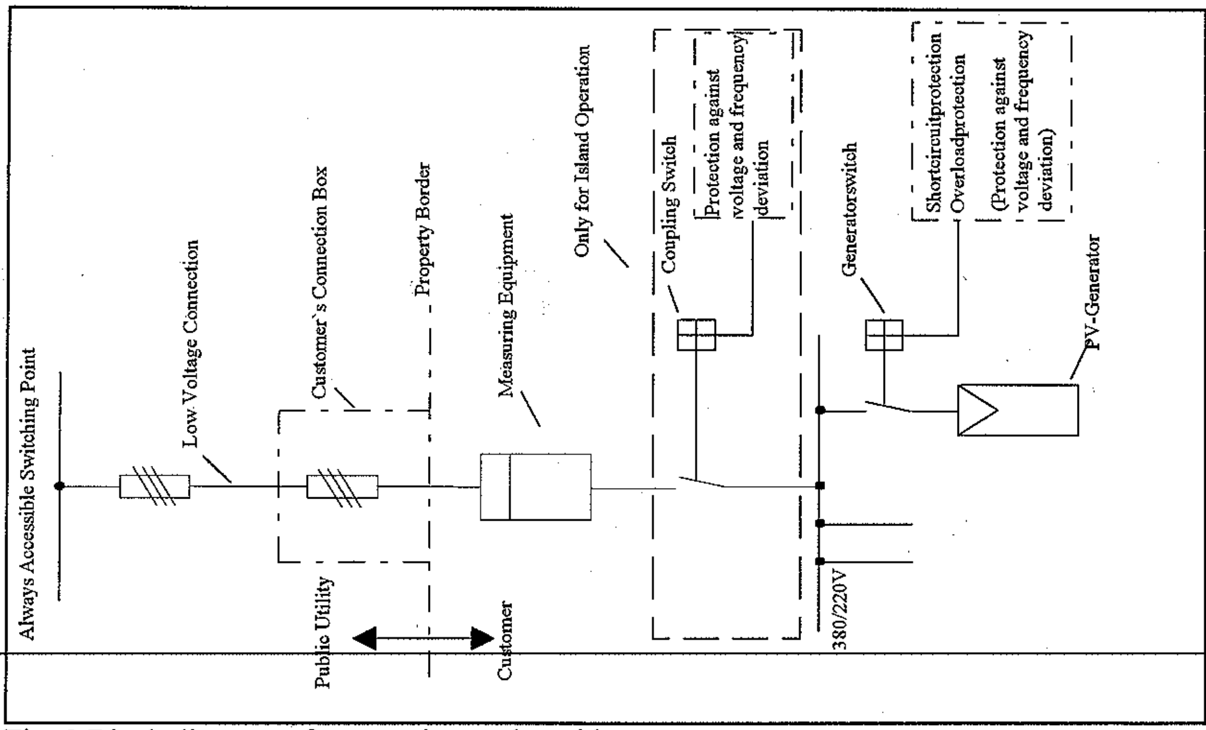


Fig. 2 Block diagram of connection to the grid

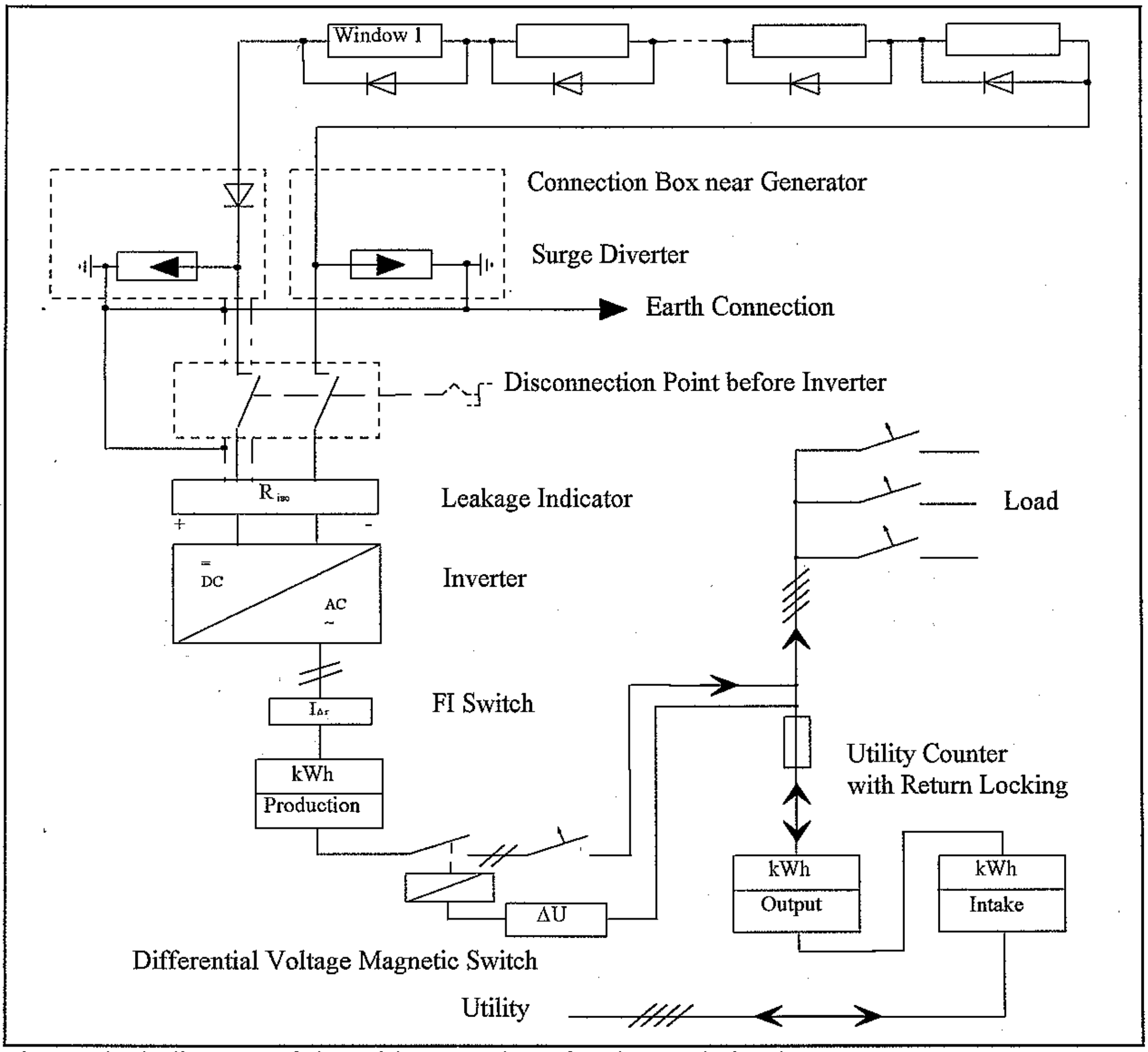


Fig. 3 Block diagram of the grid connection of a photovoltaic plant

Coming from the solar generator the cables should lead via a switching point which can separate the inverter from the generator in case of a short circuit in the inverter. In order to switch off the dc current it is not recommended to use automatic switches. They could trip unwanted in case of lightning induced overvoltages. It is better to use screw fuses for up to 600 V. The short circuit current of a solar panel is hardly higher than the operating current, therefore fuses cannot be used. Due to this it is advisable to use cables that can carry the short circuit current. The installation should be made with one-phase-cables of double insulation or with one cable put in a metal tube which will be connected to earth on both ends. The dimensioning of both, cables and switches, should be done according to the highest possible open-circuit voltage, that might occur.
In case of galvanic separation between ac and dc net (e.g. transformer) an observation of the insulation is advisable, while without galvanic separation a FI switch on the ac side is recommended. The permanent observation of the insulation resistance of an isolated net has the advantage, that in case of a single earth connection the operation of the plant will not be disturbed, but the fault will be shown and can then be repaired.
In order to guarantee a safe (voltage free) working on the grid, when switched off by the utility, an always accessible switching point is required. The switching equipment belongs to the utility and must be located outside of the customers plant to guarantee access. An exception can be made for special arrangements of the photovoltaic plant. Leaving out the for the utility always accessible switching point saves costs. However it is only allowed for single phase inverters without island operation ability in a 3-phase installation.
An inverter is able to perform island operation, if it can provide constantly a stable voltage independently of the grid state and the presence of capacitors and motors in the plant. Inverters with island operation ability can also be used for stand alone plants. The always accessible switching point is always needed for inverters with island operation ability.
Now this is not the case here. For a single phase inverter without island operation ability working in a three phase customer plant a 3-phase undervoltage relay can be used instead of the always accessible switching point which trips, if only one of the three phase to phase voltages decreases under a certain value, 1.0 to 0.7 U_n. Unfortunately this is only possible, if only one phase is connected to photovoltaic inverters in one customer plant. One or several single phase inverters with a maximum power of all together less than 5 kWp can also feed in only one phase. Additionally there has to be an overvoltage relay in every phase connected to an inverter tripping in the range of 1.0 to 1.15 U_n.
If the inverters are to feed the grid symmetrically in all phases there is no way to go without the always accessible switching point for the utility.
Also in the case of the application of the always accessible switching point overvoltage and undervoltage relays must be used to avoid damage in other customer plants during short time island operation.
After the FI switch a single tariff counter would be useful in order to get some data about the technical performance of the plant. The last thing before the grid will be the two counters belonging to the utility. They should count the power flowing only in one direction though in all three phases and additionally have a backflow locking.
For more details about the grid connection see also /3/.

3.3 Inverter for window integrated solar cells

The easiest and cheapest way of using the power from solar plants is the connection to the public grid. In that case the grid is used as an energy storage possibility. If the sun is shining and the energy is not needed (e.g. there is nobody home) the energy is fed to the grid, in case the energy demand can not be satisfied by the sun (e.g. night time) the energy can be taken from the grid.
To feed solar electricity to the grid energy conversion is needed because solar cells produce dc while in the grid ac is used. Therefore dc-ac converter (inverter) came into being. These inverters also realize a voltage transformation and automatic security and control functions like:

1. personal protection:
   - use of low DC operation voltage (<120V dc)
   - galvanic separation of dc and ac circuits by means of high frequency intermediate ac circuit
   - PV generator insulation monitoring: earth and short circuit protection
2. overvoltage protection
3. avoid electric island operation by grid monitoring
4. microprocessor controlled pulse width modulation (PWM) guarantees sinus shape current wave form which meets regulation concerning the electromagnetic compatibility (EMC) e.g. harmonics
5. maximum power point tracking (MPP) of the PV generator and automatic switch off during stand by mode to avoid loss
6. data acquisition and default indication

Inverter have usually a relatively constant loss (around 8 % of the nominal power) and a smaller heat loss (2-5%) of the power electronic switches depending on the current. Due to the dominant constant loss it is advisable to run an inverter close to the nominal power.
The solar cells chosen are of lower quality and give a nominal electric power output of around 1,1 Wp (Wattpeak), which is the output under a radiation of 1000 W / m^2 and 25 °C. The output under real environment conditions is even less. To get higher power many solar cells are connected. Serial connection increase the output voltage while parallel connection increase the output current. Typically 36 solar cells are connected in serial and mounted to an e.g. 50 Wp module. The modules are again wired in serial to so called strings to get the desired voltage while the strings can be wired in parallel to get the desired power output.
Commercial inverter are designed to be connected to certain number of PV modules. In the last few years special small scale inverters were designed e.g. "Sunny boy" for 6 - 10 PV-modules and the "OKE4" inverter for up to 72 cells (1 - 2 modules).
In order to reach a high efficiency a good matching between PV generator and inverter is needed.
The PV generator at the Skibsted Fjord training center is orientated to 4 different directions. Therefore the radiation is different depending on the sun position. The electric current output of the solar cells is directly proportional to the radiation. So the solar cells which get momentary less radiation can produce naturally less current. Because of serial connection the weakest solar cell determines the string current. The current cannot flow around one cell but through the connection (fig. 4), so it must be equal in all cells. Therefore differently orientated (or shadowed) cells should not be wired in one string.

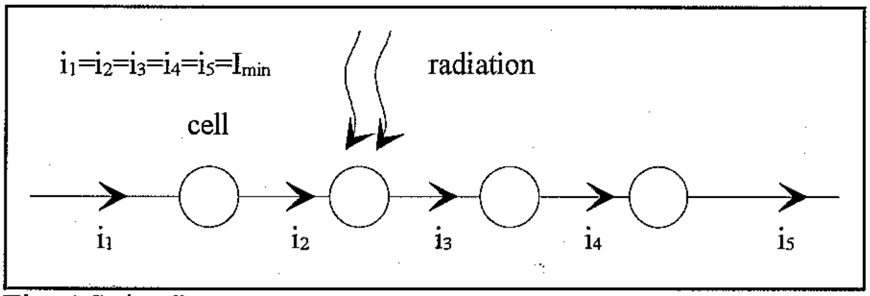


Fig. 4 String Part

Due to the demonstration character of the plant it was decided to use independent inverters for each window front. So the relationship between sun radiation and power output can be directly observed. There are 4 window areas at the Skibsted Fjord training center with different orientations. According to the pattern chosen the number of solar cells is given:

- The restaurant area orientated to south east, fig. 2: 588; fig. 3: 614 cells
- the entrance area around the hall to south is divided into 2 parts (see App.) with 9 windows, 332 cells =365 Wp (316 cells = 347 Wp) and 8 windows, 288 cells = 316 Wp (304 cells = 334 Wp depending on the pattern)
- The schooling room area to southwest, fig. 13: 696 cells

For the smallest number of 288 solar cells the following calculations can be made to find out whether to use a Sunny boy inverter or some OKE4 instead:
The sunny boy is designed for up to 750 Wp input while the OKE4 is for 100 to 130 W. Therefore 3 OKE4 inverter are needed to cover the 316 Wp of the 288 cells.

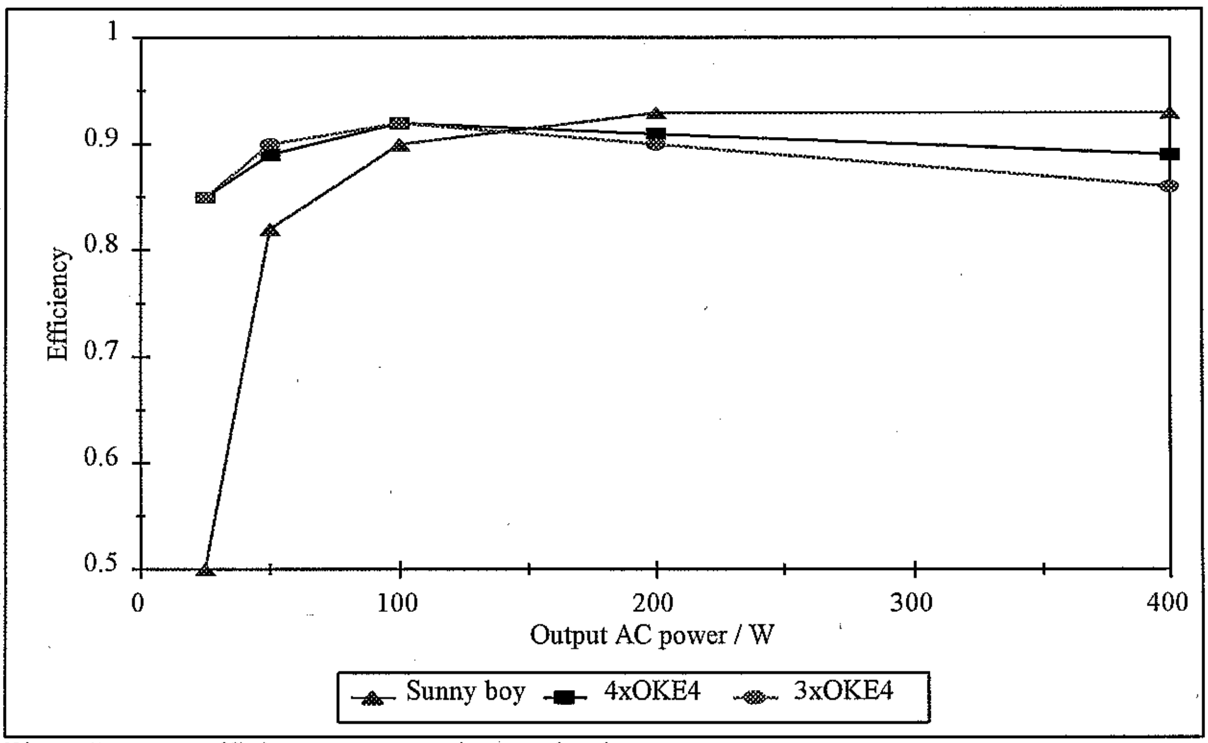


Fig. 5 Inverter efficiency compared to total values

Fig. 5 shows, that the Sunny boy has a rather bad efficiency in the lower power range while it's efficiency raises with the power and exceeds the OKE4 at around 200 W. Due to the PV-power expected being a little less than the rated output even under good irradiation conditions and much less under poor weather conditions the OKE4 will be the better overall choice.

Economical aspects:
For the 2 entrance plants 6 OKE4 or 2 Sunny boy are needed. Minimum order size for the OKE4 is 10, single OKE4 kits are available for a higher price (October 1995):

number	type	max. power/ W	price per piece / DKK	price per power / DKK / Wp	total price / DKK
6	OKE4 kit	130	2000	15,3	12000
10	OKE4	130	1200	9,2	12000
2	Sunny boy	750	8000	10,7	16000

Table 1 : Investment comparison

The total investment for the OKE4 is lower. Additionally the specific price/Wp is lower when using the 10 piece order with discount. It can be suggested for the case that the remaining 4 OKE4 inverter can be used for something else.

3.4 Installation

It should be mentioned here, that installing photovoltaic panels needs a special care. Due to the light at working time there will always be a voltage on the terminals. The so called working on higher voltage than 50 V ac or 120 V dc demands a certain organization, especially trained workers, special tools, but first of all an awareness of the fact. Some points which will have to be considered are
- special marking of the place
- what to do in case of an accident
- awareness of possible danger and behavior
- restricting conditions (safe stand, weather, visibility)
- insulating gloves, etc.
- insulated tools (spanner, screwdriver, voltage detector, mats, cover material)
- reduction of short circuit power (separation of net parts, fast fuses)

During the installation it is important to support some of the protection mechanism. So it is advantageous to have a meshed earth network and connected to it the module frames (of panels) as well as the skeleton, metallic covers, active parts and the surge diverters.
In order to minimize lightning induced overvoltages some constructional measures have to be considered. The wires or cables should not be arranged in a loop (fig. 6). The panel strings could be placed meanderingly for the induced overvoltages to compensate themselves in the neighboring strings or have the two wires placed in one cable (fig. 6). The panel frames should be connected to whatever metal roof or bodies are nearby to prevent the occurrence of capacitors as well as to metal mantles of cables.

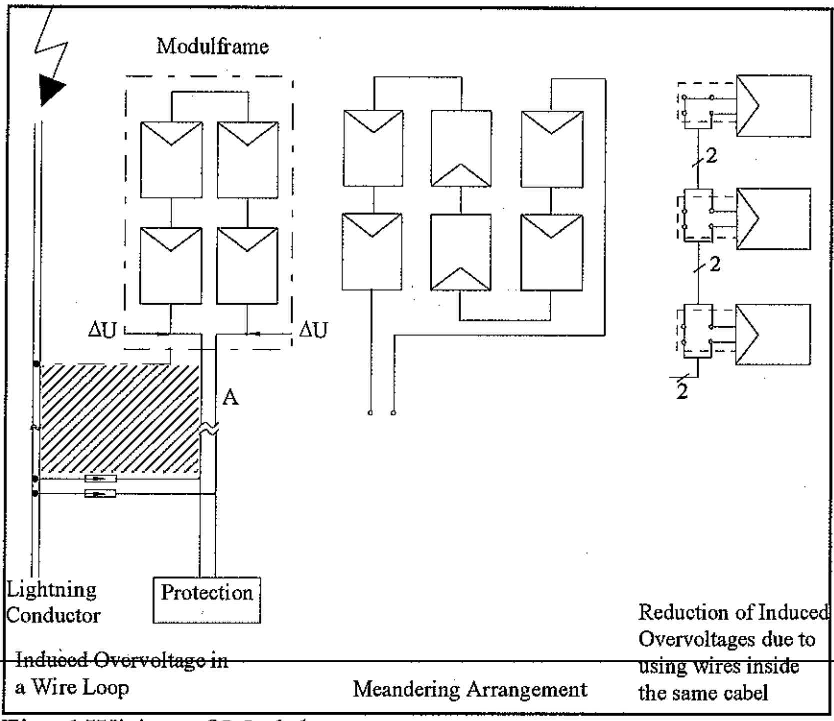


Fig. 6 Wiring of Modules

3.5 Conclusions

As shortly mentioned above the inverter used will perform all the protection functions demanded. They will continuously monitor the net. The OKE4 will monitor both frequency and voltage and as soon as the inverter is disconnected from the grid, it switches off automatically within 0.1 second (no island operation). Since the dc input voltage (max. 40 V) is lower than 120 V (protective low voltage) and even lower than the 60 V limit, no protection against direct touch will be necessary. Dc and ac side are electrically isolated. The inverter will be installed directly on the panel meaning no switch in-between. It also meets the EMC VDE0871 standard for electromagnetic compatibility. The OKE4 has additionally an internal kWh counter which can be read out by means of a PC. Now the Sunny Boy offers similar features. It monitors the grid continuously including impedance measurement, includes galvanic separation, earth fault monitoring, overvoltage protection and of course it meets the regulations concerning the electromagnetic compatibility according to EN 50081, part 1, En 50082, part 1, EN 60555 and EN 55014 (grid interference) . Therefore
it can be connected to an existing distribution at any place. Due to the galvanic separation, the low short circuit current and the low voltage (protective low voltage) an external switch on the dc side is unnecessary. Communication with the inverter including power counting is possible via the existing mains lines and a modem connection to a PC.
Due to the features offered by the inverters chosen the installation will be very simple and reliable.
Since the maximum power of all single phase inverters does not extend the 5 kWp they can all be connected to one phase leaving out the extra, always accessible switching point for the utility.
The only thing which has to be investigated further is the counter with backflow locking that will have to be used.
As mentioned before this plant is meant to be a demonstration for solar cell integrated facades. If it causes more people to think about new designs as well as environmentally friendly use and production of energy its purpose will be fulfilled.

4 References

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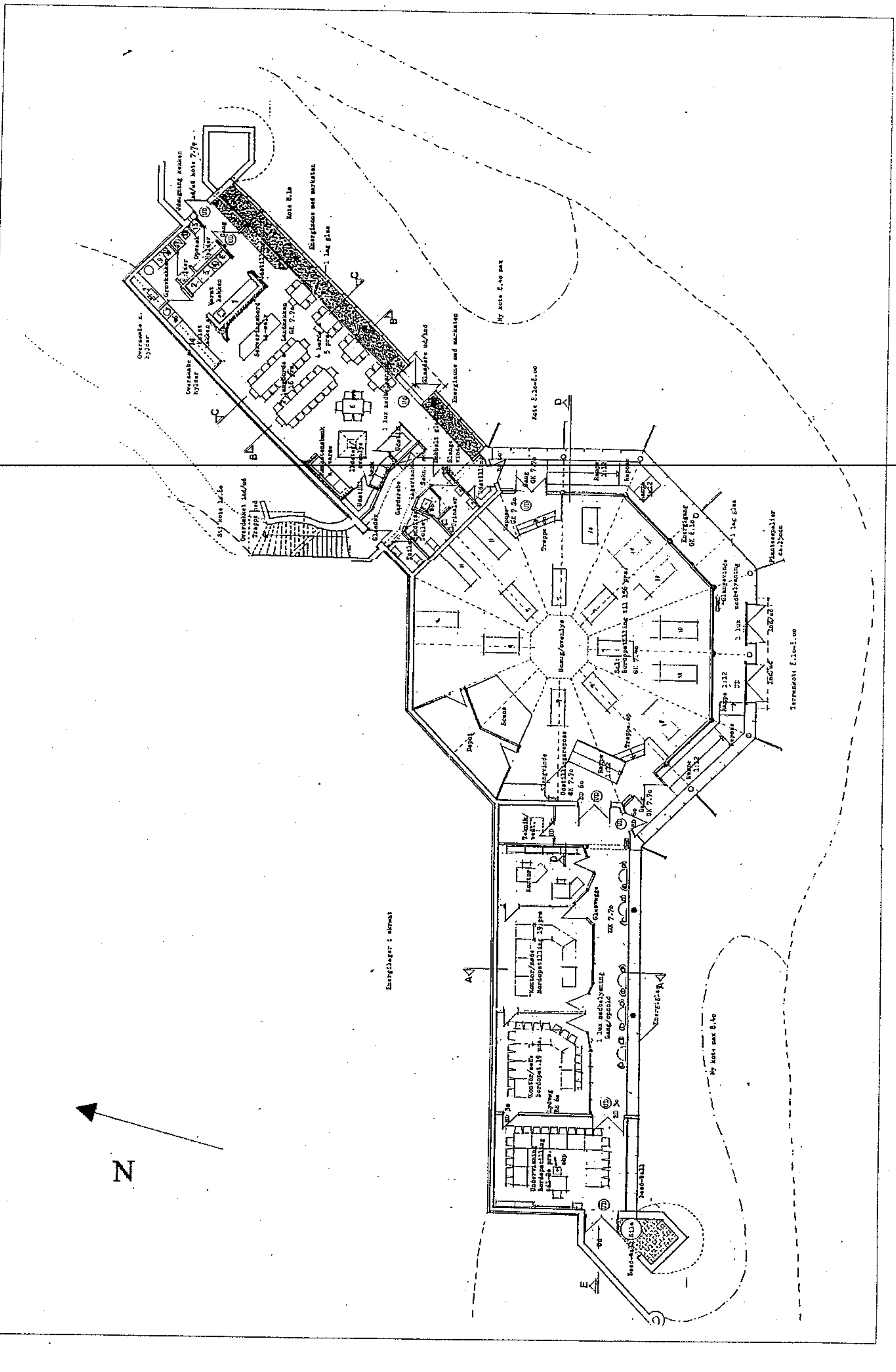
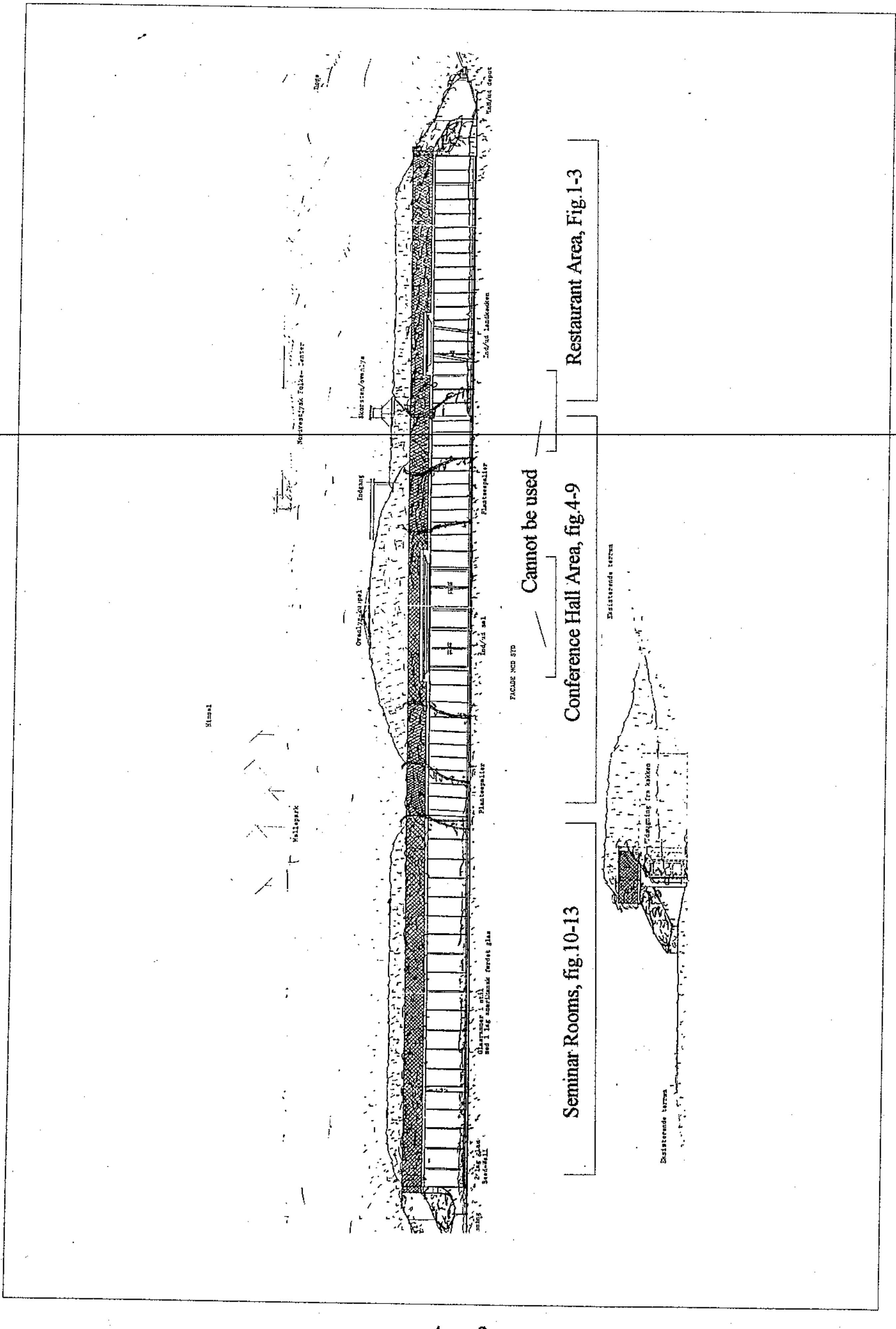
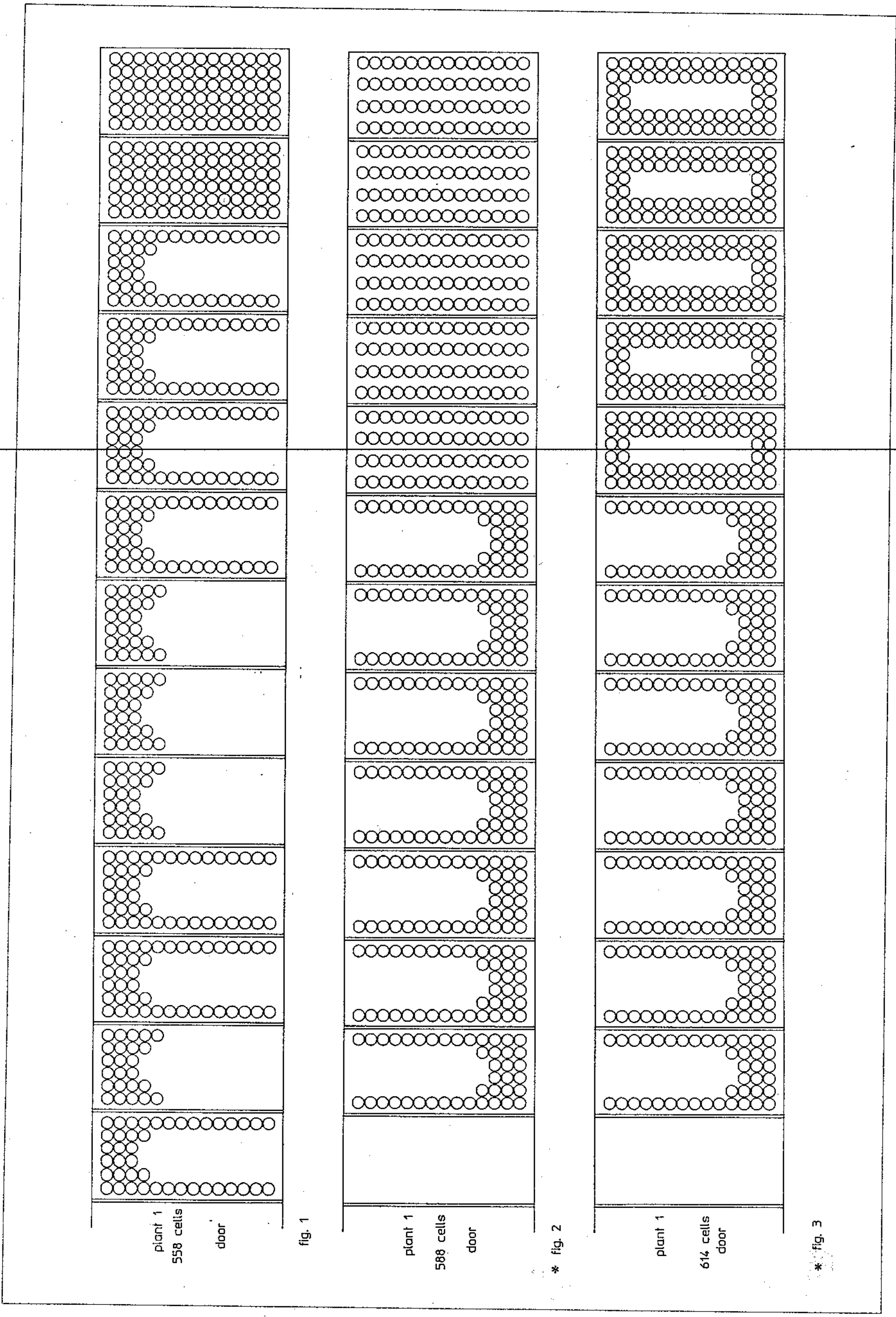
5 Appendix

App. 1:	Cross Section of Skibsted Fjord Training Center
App. 2:	Front View of Skibsted Fjord Training Center
App. 3:	Fig. 1- 3; Plant 1: Proposals for Restaurant Area
App. 4:	Fig. 4- 9; Plant 2: Proposals for Hall
App. 5:	Fig. 10- 13; Plant 3: Proposals for Seminar Rooms



App. 1


Restaurant Area, Fig.1-3
Cannot be used
Conference Hall Area, fig.4-9
Seminar Rooms, fig.10-13
FACADE MOD SYD
Himmel
Indgang


plant 1
558 cells
door
fig. 1
plant 1
588 cells
door
* fig. 2
plant 1
614 cells
door
* fig. 3

App. 3

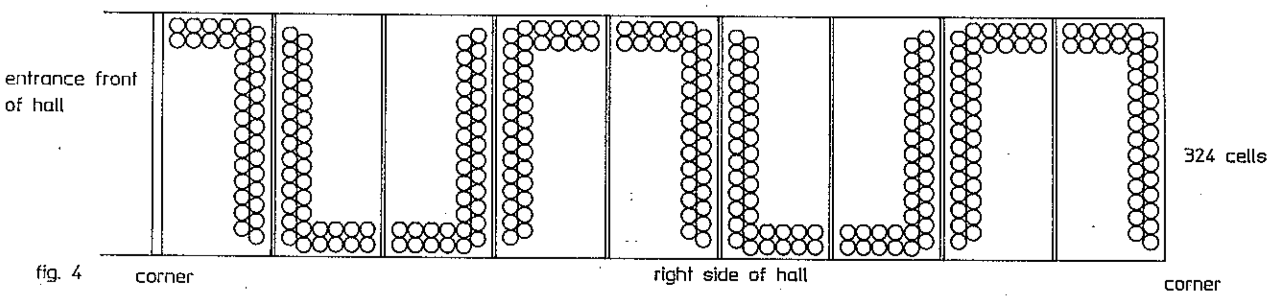


fig. 4

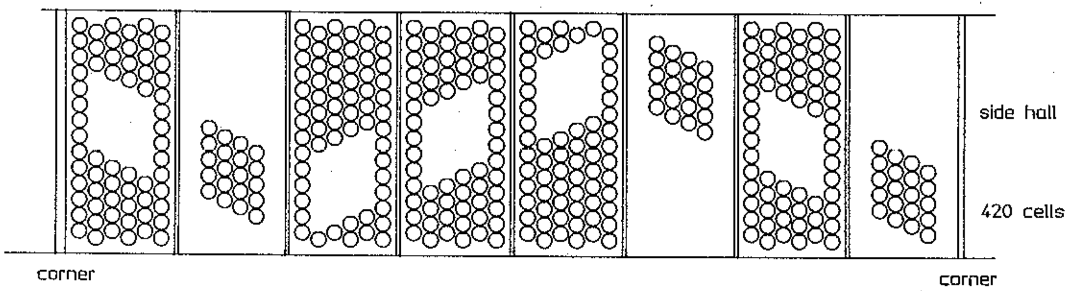


fig. 5

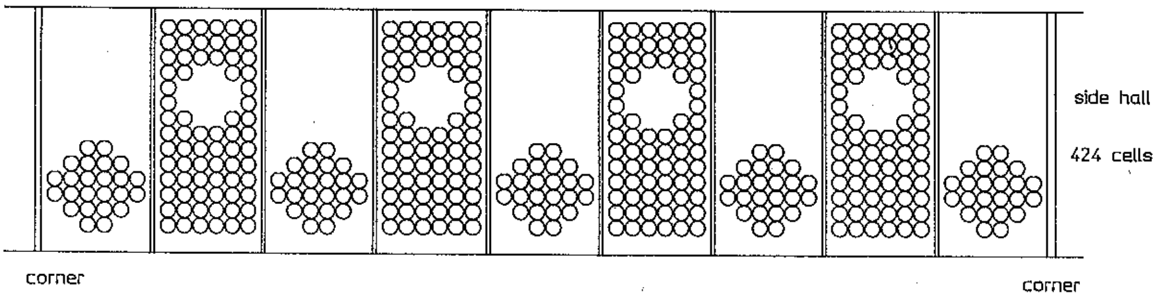
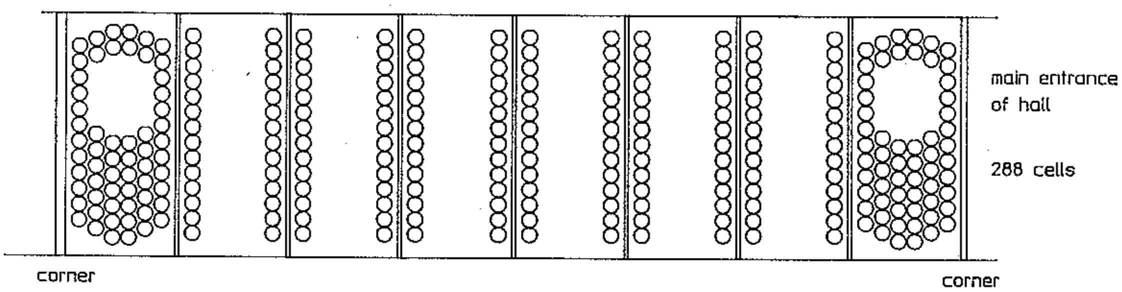
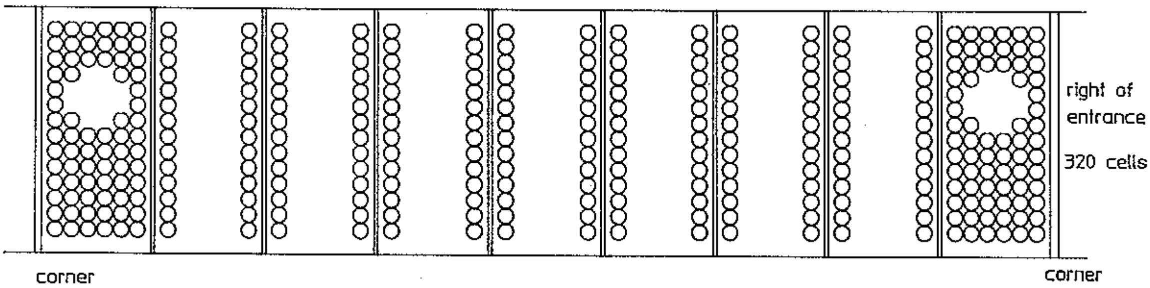


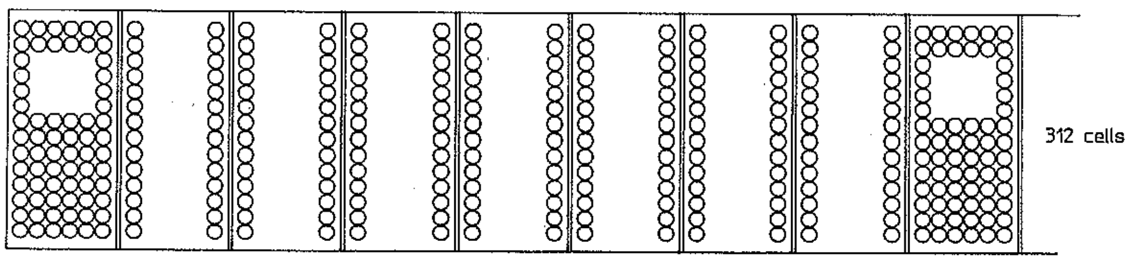
fig. 6



* fig. 7

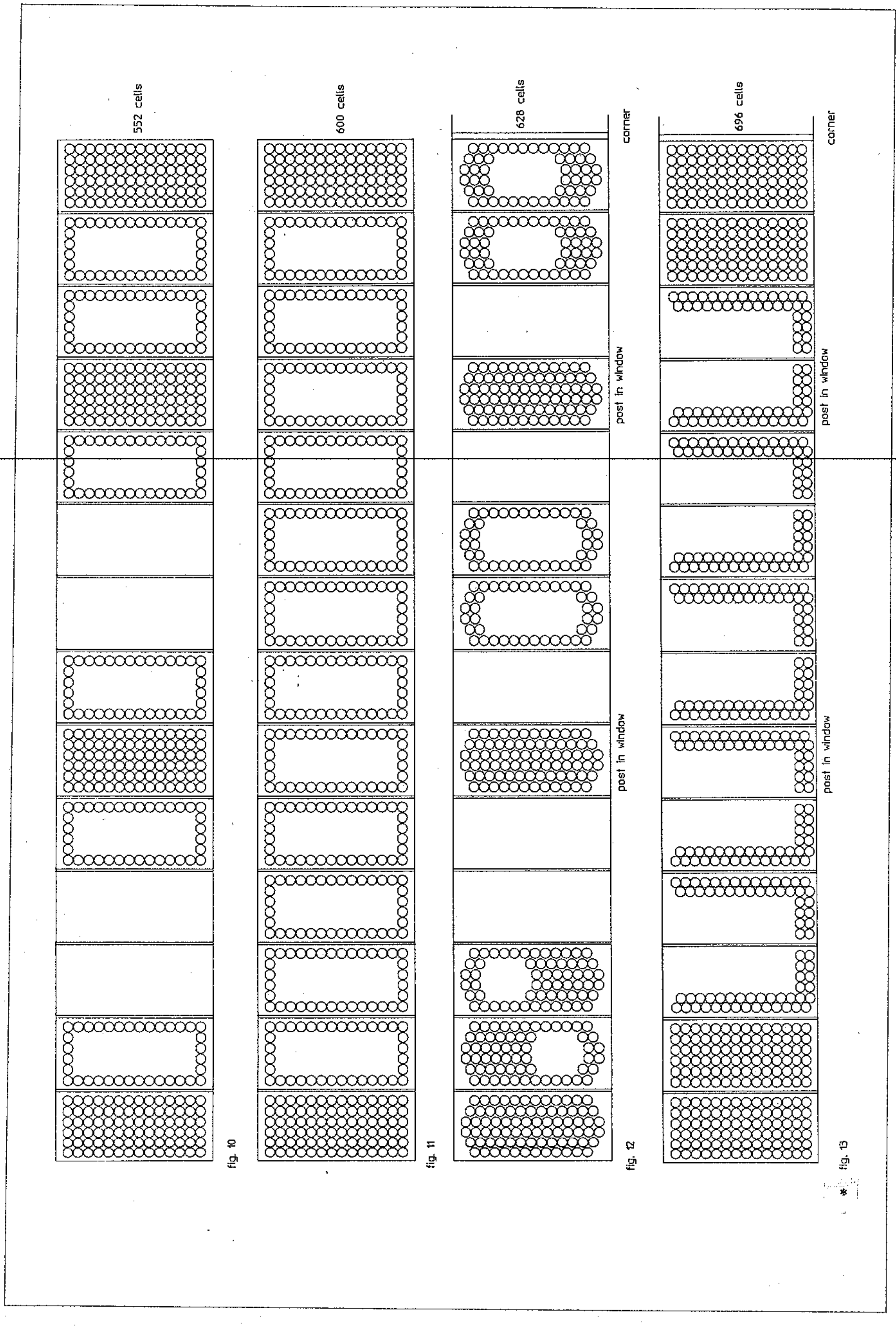


* fig. 8



* fig. 9

App. 4


552 cells
600 cells
628 cells
corner
696 cells
corner
post in window
post in window
post in window
post in window
fig. 10
fig. 11
fig. 12
fig. 13