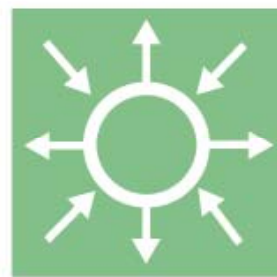


# Benefits of interconnecting stand-alone PV into a mini grid

Case Study: Vidinge, Stockholm archipelago

Elforsk rapport 06:78



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**ELFORSK**

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## Förord

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Rapporten finns fritt nedladdningsbar från SolEI-programmets hemsida:  
[www.elforsk.se/solei](http://www.elforsk.se/solei).

## Sammanfattning

Syftet med denna studie har varit att studera tekniska och ekonomiska fördelar med att koppla samman enskilda soelförsöjda fastigheter i ett mini-elnet. En del av uppgiften har varit att undersöka vilken utrustning som krävs för en sådan ihopkoppling och vad som finns tillgängligt på marknaden.

Den bärande idén är att ett gemensamt elnet på olika sätt skulle göra mer energi tillgänglig för användarna. Överskott som produceras i en solcellsanläggning vid en fastighet kan nyttiggöras av andra fastigheter i närheten. I och med att nätets kablar sträcker sig över ett större område öppnas nya möjligheter för placeringen av solcellsmodulerna. Dessutom kan flera hushåll dela på investeringskostnaden för en gemensam utökad produktion, t.ex. i form av en vindgenerator.

En målsättning har varit att genom praktiska exempel visa på strategier, möjliga tekniska lösningar och olika alternativa genomföranden samt att utvärdera dessa.

En strategi har formulerats som ska utgöra en bra utgångspunkt för uppbyggnaden av ett mini-elnet.

- Varje delägare ska ha en effektiv produktionsanläggning dimensionerad för det egna toppeffektbehovet
- Vars och ens batteribank ska vara anpassad till egen solcellsproduktion
- Var och en ska kunna ladda sina batterier från nätet när överskottsström finns tillgänglig
- Inkommande ström bör begränsas i proportion till respektive hushålls egen genomsnittliga produktionskapacitet
- När det egna behovet är tillgodosett och batteriet har nått en överenskommen laddningsnivå ska producerat elöverskott matas ut på nätet (stys av en lokal kontrollenhet genom att t.ex. mäta batterispänningen)
- Den som har dåliga förutsättningar för solinstrålning ska kunna investera i solceller som monteras på någon annans byggnad eller gemensam plats.
- Effektmätning bör ingå dels för avstämning av att överskott och gemensamt producerad ström fördelas rättvist, dels för att det möjliggör att finna felaktiga enskilda anläggningar som kan dränera nätet.

Inga regulatorer har hittats på marknaden som har funktioner för att dels begränsa inkommande ström, dels koppla om strömmen (från att exempelvis mata ett batteri till att mata ut på nätet). Båda funktionerna har påträffats var för sig i olika sammanhang, men inte i önskad kombination.

Den ekonomiska utvärderingen är baserad på förhållandena för 12 fritidshus på en icke-elektrifierad ö i Stockholms skärgård, Vidinge. Resultaten kan dock översättas till liknande bostadsgrupper på andra håll, som ligger samlade inom en radie av 50-200 meter.

Mot bakgrund av den allmänna tekniska utvecklingen och en enkät till de boende på Vidinge så har ett antal nivåer på elstandard definierats. Nuvarande elbehov och boendemönster på Vidinge samt förväntade eller önskade förändringar i detta har inventerats. För varje elstandard-nivå har en individuell solcellslösning dimensionerats, inkluderande solceller, batteribank och ett eventuellt elverk. Ett mini-nät har sedan dimensionerats för samtliga alternativ. Slutligen har investeringskostnaden för alla alternativ tagits fram

för en kostnadsjämförelse. Även en kostnad för anslutning till allmänna elnätet har tagits med i jämförelsen.

För att utvärdera vinsten med att kunna fördela energiproduktionen via ett mini-nät så har Energibanken tagit fram ett Excel-program. Beräkningar för Vidinge-fallet presenteras som ett exempel. Energivinsten har beräknats baserat på boendemönstret på Vidinge, men med elbehov enligt en av de generella elstandard-nivåer som tagits fram. För ett fall med 5-6 hus kommer då 15-20 % mer av producerad energi till nytta via mini-nätet. För fallet 12 hus är motsvarande vinst ca 30 %. Dessa vinster äts emellertid till stor del upp av de energiförluster som uppkommer i nätet, i kablar, omformare och kontrollutrustning.

I Vidinge-fallet skulle en värdefull vinst med ett mini-nät vara att solcellsmoduler kan placeras på platser med bättre solinstrålningsförhållanden, eftersom stora problem med t.ex. skuggning förekommer. I en jämförelse av investeringskostnaderna för mini-nätlösningen kontra fristående anläggningar visar det sig dock att mini-nätet inte ger någon ekonomisk vinst, ens med hänsyn tagen till detta.

Kostnaden för nätet utgörs till två tredjedelar av kabelkostnaden. På grund av höjda koppar- och aluminiumpriser på världsmarknaden så har priserna på elkabel ökat med upp till 100 % på ett år. Det är en kraftig förändring av förutsättningarna jämfört med gällande förhållanden när denna studie kom till, och det har en kraftig inverkan på kostnadsresultaten. Men den förväntade prissänkningen för solceller innebär också den att sammankopplingen i ett gemensamt nät kommer att bli en mindre lönsam lösning, jämfört med egna, fristående anläggningar.

Andra fördelar understryks av Vidinge-fallet. De verkliga förhållandena visar tydligt hur svårt det kan vara för en fastighetsägare att hitta en optimal placering för solcellsmoduler. Det har visat sig att möjligheten till bättre lokalisering av moduler och att investera i en gemensam utökad produktion värderas högt. Det är sådana skäl som kan motivera ett mini-nät snarare än energivinsten.

Kostnaden för anslutning till allmänna elnätet via sjökabel ligger i Vidinge-fallet i samma storleksordning som kostnaden för en fristående lösning med solceller, batteri och elverk som är dimensionerad att motsvara nätanslutningens elstandard. Avståndet till det allmänna elnätet är i detta fall ca 9 kilometer. Kostnaden är ungefär två till fyra gånger så hög som för ett klenspänningsalternativ som dimensioneras för en lägre nivå på elstandard, men som ändå uppfyller de boendes krav.

Ledningarna i mini-nätet har dimensionerats med hänsyn till spänningsfall och energiförluster. Det har visat sig att samma kabeldimensioner krävs i 24 Vdc-systemet, som elbolagen använder i ett 230 Vac-system. 24 V-alternativet förslås därför utföras i enlighet med regelverket för 230 V lågspänningssystem. På så sätt blir säkerhetsfrågor hanterade på ett riktigt sätt, och eftersom det finns en stor marknad för material och utrustning för 230 V så är det också kostnadseffektivt att genomgående välja denna standard.

Ett markförlagt nät med systemspänning 24 V eller 48 V (vilket innebär en tomgångsspänning under 110 V) bör fastighetsägarna kunna utföra och sköta

i egen regi. Alternativet med 230 V systemspänning rekommenderas inte på grund av den avsevärt högre kostnaden, som följer av att de svenska föreskrifterna kräver att behörig installatör anlitas och att nätkoncession krävs.

Under arbetets gång har det varit oklart i vilken mån privatpersoner har rätt att dra en starkströmskabel över tomtgränsen. Om detta inte är tillåtet så innebär det att en privatperson inte kan placera solcellsmoduler utanför den egna tomten, även om samma person äger denna mark. För att detta inte skall vara ett hinder för installation av solel bör det tydliggöras att det är tillåtet att distribuera klenspänd starkström utan krav på nätkoncession om det sker utan kommersiellt syfte.

Att få till stånd ett mini-nät i ett demonstrationsprojekt bedöms som intressant för att utreda praktiska och tekniska frågeställningar och lösningar vidare. Inte minst vore det intressant att belysa regelverk och lagar kring en lokal småskalig samverkan om elproduktion, och de kostnader som de för med sig. Intresset för en sådan här typ av samverkan förväntas kunna öka i och med ökade kostnader för att vara ansluten till det allmänna elnätet, samtidigt som alternativ el-generering blir alltmer tillgänglig. Det kan gälla fritidshusområden men också fastboende som befinner sig i elnätets utkanter.

Som litteraturstudien visat finns ännu relativt liten erfarenhet av småskaliga elnät som omfattar distribuerad förnybar produktion, även utanför Sverige. Ett demonstrationsprojekt på hemmaplan skulle inte bara ge Sverige kunskap att dra nytta av för egna förhållanden. De tekniska lösningarna kan ge värdefulla erfarenheter som kan överföras på många skilda situationer och t.ex. vara användbara i utvecklingsprojekt i u-länder som Sverige arbetar med.

För att realisera ett mini-grid enligt denna studie bör en regulator med inbyggd strömbegränsning och strömshunt utvecklas. En sådan skulle för övrigt ha en funktion att fylla även i enskilda solcellsanläggningar, där den bland annat skulle kunna underlätta flexibel utökning av produktionskapaciteten med fler moduler och/eller annan produktion.

## Summary

The objective of this study has been to investigate the possible economical and technical benefits involved with the interconnection of a group of off-grid households with individual PV-power supply. Part of the task has been to examine what technology is needed to connect the units and what is available on the market.

The central idea is that a communal power grid connecting houses with individual stand-alone PV-power supply would make more energy available to the users. Excess power generated in one site could come to use in another. A better choice of suitable sites for installing the PV-panels might be found, with the extended cables of the grid. Several households may share the cost for built out power supply in the form of a communal installation, e.g. wind turbines.

The intention has been to show – by means of practical examples – strategies, possible technical solutions and ways to build such a network. The intention was also to evaluate the mini-grid solutions, put in relation to alternative power supply options.

The following strategy has been found to make out a good starting-point for the design:

- Each part-owner is to match the battery to the PV-modules in his/her own installation
- Each part-owner is to have an efficient power generation installed, corresponding to his/her peak power demand
- The part-owners may always charge their batteries with current from the grid, when available
- Incoming current is to be limited to stand in proportion to the mean power of the PV-modules of each household
- The part-owners are to supply power to the grid when their battery has reached an agreed level of charge (controlled by the local control unit and by measuring the battery voltage, for example)
- A part-owner with poor irradiation conditions may put up modules on an existing common building or another site
- Measuring the energy consumption drawn from the grid by each user gives increased possibilities to fair distribution. It also makes it possible to detect faulty batteries that may be using excess energy for no use. A faulty battery that is no longer rechargeable may lower the grid voltage so that the other batteries risk to receive no power at all.

Regulators with a limiting function for incoming current and for redirection of excess power (e.g. from feeding a battery to feeding the mini-grid) are not available on the market. The functions seem to exist separately in different contexts, but not in the desired combination.

An outline of how the grid may be built and how the above demands may be satisfied is given in the report.

The economical evaluation is based on the conditions for a group of 12 houses on the non-electrified island of Vidinge in the Stockholm archipelago, however can be translated to other, similar groups of properties that are situated within a radius of 50 – 200 metres.

A number of levels of electrical "standard-of-living" have been established, based on the general technology development in combination with an enquiry among the home owners on Vidinge. Present power demand and utilization times and expected or desired changes was surveyed. Stand-alone power supply has been designed for each standard level, consisting of PV, batteries and possible supplement of a diesel or petrol generator (gen set). A mini-grid has been sized for the different alternatives. Finally, the total investment cost has been established for all alternatives, compared also with the option of connecting to the mainland grid.

In order to evaluate the benefit of energy distribution in the mini-grid, Energibanken has set up an Excel-program. Calculations for the Vidinge case serve as an example. The "energy gain" has been calculated on the basis of residency times at Vidinge, but carried out for general energy demand according to one of the established levels of electrical standard. For the case of 5-6 houses 15-20 % more energy will be made useful and for the case of 12 houses the gain will be around 30 %. However, this gain will be largely lost through the added energy losses in the network; cables, converters and control equipment.

In the Vidinge case, the substitution of problematic sites for PV (e.g. shading) for sites with better conditions, would be a valuable benefit of a mini-grid. Even under these circumstances the investment cost comparison (August 2006) shows no economical benefit of building a mini-grid compared to individual plats.

Two thirds of the cost of the network is made out of cable costs. Due to increased costs of copper and aluminium on the world market, cable prices have risen by up to 100 % in a year. This is a dramatic change of situation from the time this study was first conceived and it has a strong impact on the cost result. However, the expected cost reduction for PV, as well, will cause the mini-grid to become a more unfavourable solution compared to individual PV-plants.

Other benefits have been underlined by the Vidinge case. The situation in the real case shows with clarity how difficult it may be for a house-owner to find an optimal placing of PV-modules. It has been found that the possibility to find better sites for PV-installations and to share the investment cost of a built out power supply with others, is highly valued. These are the reasons that would motivate a mini-grid, rather than the energy benefit.

A connection to the main power grid on the mainland via sea cable is estimated to equal the investment cost of a stand-alone solution designed for "main grid" electrical standard. The distance to the main grid in this case is around 9 kilometres. The cost is two to four times higher than that of an extra-low voltage alternative sized for the electrical standard that has been found to be sufficient for peoples needs in the case study.

The cables have been sized with regards to voltage drop and energy losses. It was found that the cables for the 24 V system voltage will be of the same size as cables for a 230 V connection to the main grid. It is recommended that the 24 V-grid design be built in agreement with the regulations for 230 V low-voltage systems. That way, issues of safety are handled properly, and since

there is an important established market for material and equipment it will also be cost-effective.

A ground-laid network with a system voltage of 24 V or 48 V (i.e., open circuit voltage below 110 V) should be possible for the house-owners to build and manage themselves. 230 V system voltage is not recommended because of the considerably higher cost, which is due to the regulations that require a licensed installer and network concession.

During the course of this study it has been unclear what right a private person has to lay heavy current cables outside the own block of land. Should this not be approved, it means that a private person can not place PV-modules outside the own block of land, even if he/she owns the piece of land too where the modules are placed. For this not to be an impediment for PV-installations, it should be clarified in the regulations that distribution of extra-low voltage heavy current is allowed, without need for network concession, when the purpose is purely non-commercial.

It would be of interest to install a mini-grid for demonstration purposes, in order to further explore the practical and technical implications and solutions. This type of collaboration between neighbours, in vacation home areas but also among permanent residents in remote locations, is believed to become of growing interest in the future as the cost of main grid power supply increases and the alternatives become more available.

As the literature study shows, experiences of small scale power grids that comprise distributed renewable generation are limited. A demonstration project would not only build useful knowledge for the Swedish circumstances. The technical solutions are in many ways transferable to other situations and valuable experience could be gained e.g. for projects in developing countries where Sweden is engaged.

A regulator with built in functions for amperage limitation and current redirection should be developed – this would be of use not only in a mini-grid context but in built out stand-alone solutions as well.

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## Appendices

Appendix A. Inventory of the houses at Vidinge

Appendix B. Inventory of equipment and appliances, expected changes and conditions for solar power at each house respectively.

Appendix C. User patterns in the Vidinge case

Appendix D: Power consumption of electric appliances

Appendix E: Choice of cable and other network components

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# 1 Introduction

## 1.1 Background

Many people in Sweden react to the cost of connecting remote properties to the national power grid. The cost of connection may be as high as SEK 150.000 per kilometre. Even if several properties share the cost, there will be a significant cost for each one. The alternatives are stand-alone power plants, often with a combination of diesel or petrol generators, PV modules and wind turbines.

Amongst other things, heavy storms have in recent years pointed to the risks regarding security of power supply for remote households. Very high costs may be associated with the restoration of power supply and the repair times can be lengthy. For some, back-up power of their own is a necessity (e.g. farming properties). Where this is the case, the question of disconnecting from the national grid altogether may become relevant.

In Sweden, there are numerous off-grid power installations for remotely located vacation homes. In many of these cases small PV-systems have been economical for a long time. Today, a change in the consumption pattern in this user category has been noted. Lighting that has traditionally made out the base load, is starting to be exchanged for LED-lights which drastically cut the energy need for lighting. On the other hand new electric appliances are being added and used during longer periods of time (for example computers, TV). A general wish for a higher electrical standard seems to be common, adding consumers like water pump, vacuum cleaner, toaster. Combined, it impacts power demand by reducing the base load and increasing the amount and amplitude of power peaks.

The cost of a PV plant may rapidly become of considerable importance for a household when demand is increasing. Also, on the property of a small vacation home it may be difficult to build out a PV installation without making unacceptable impact to the local environment, or it may be difficult to find a suitable place altogether. In this context, the idea was born to explore the possible advantages for a group of off-grid households to "join forces" by connecting to a small communal power grid.

By co-operating in a small common grid, a group of households might share the investment cost for added power supply; they may find more favourable sites for PV-modules; excess power from the plant of one household is made available to others.

It is however not obvious how such an installation should be realized, technically nor practically. In the Swedish context, there seems to be little or no experience of questions regarding this type of small scale co-operation in a power grid and of what benefits and synergy effects it may present.

## 1.2 Objectives

The present study has several objectives;

- To show available technology and the possible economical and technical benefits involved with the interconnection of a group of off-grid households with individual PV-power supply;
- To identify possible demands for development or complement of components that might be needed to realize the mini-grid;
- To make a cost comparison between a mini-grid solution and other, more traditional, power supply solutions.

### 1.3 Method

First, a literature study has been carried out, in order to collect relevant information (internationally and from Sweden). This has led to suggestions for the development of new components which were found to be needed to form the intended mini-grid.

The study has been carried out as a theoretical case study, by reviewing the conditions regarding power demand, supply, local environment etc., on a non-electrified island in the Stockholm archipelago. Today, there are only vacation homes on the island, and there are various stand-alone power solutions. Different alternatives for building out power supply to meet increasing demands are being discussed among the owners, one of the options being connecting to the mainland grid via sea cable.

By means of a questionnaire directed to the owners, the present conditions and expected changes in power demand and residency have been determined.

On the basis of this, a number of general levels of electrical standard have been chosen. Stand-alone power supply have been designed for each level, consisting of PV, batteries and possible gen set supplement. A mini-grid has been sized for the different alternatives, based on the layout conditions of the studied island. The total investment cost has been established for all alternatives, compared also with the option of connecting to the mainland grid.

An excel programme has been set up in order to determine the possible energy benefit presented to the part-owners by the mini-grid, thanks to differences in residency times. The benefit has been calculated for one of the electrical standard levels, for the residency times of the case study, to illustrate the possible gain in a "real case".

## 2 Literature study

A literature study has been carried out which covers:

- Description of and experiences from existing installations and studies concerning so called mini-grids, where photovoltaic (PV) power makes out the power source, alone or in combination with other energy sources.
- Components available in Sweden that can be used to build a mini-grid.

### 2.1 Relevant experiences - internationally

A mini-grid connects several households to one or more sources of electric power. The conventional sources of power in existing mini-grids are diesel generators.

There are a number of examples around the world of diesel-based mini-grids where PV is used as a supplementary source. An aim in these projects is often to design the system so that battery-capacity is avoided, in order to keep installation costs down [9]. Here, the emphasis in current work lies on solutions for the diesel generator sets (gen sets) to balance the PV production and the demand of the load.

In a small but growing number of mini-grids the PV-generators make out the prime source of energy, either in combination with battery storage solely or in combination with other energy sources.

For all mini-grids, the conventional solution today is centralized power generation. More recent is the development of different solutions and configurations of distributed power sources in the mini-grid.

#### 2.1.1 IEA-PVPS

The Photovoltaic Power Systems Programme (PVPS-programme) is a collaborative R&D Agreement, established within the International Energy Agency and conducting projects on the application of solar photovoltaic electricity. IEA- PVPS operates worldwide via a network of national teams in member countries.

##### Stand Alone Photovoltaic Applications – Lessons Learned

The work within IEA-PVPS Task 3 is focused on stand-alone PV applications. The most recent "state-of-the-art" report within this framework was published in 1999: "Stand-Alone Photovoltaic Applications – Lessons Learned" [1]. The publication treats different aspects of stand-alone PV systems (SAPV), which are divided into three categories; service applications (typically appliances with low energy demand); remote buildings (typically one household, 50 – 2000 Wp) and larger island systems (10 – 100 households).

The report states that the island application at the time was the least developed of the three categories on a market and systems level, and that

many questions remained to be resolved in order to move the application forward. Issues mentioned are sizing, economics, power and load management, management of the communal power supply and individual domestic power consumers.

The report particularly points to the social aspects of multi-user systems. It is argued that the most difficult point in the implementation of multi-user systems is to combine the interests of the potential users. Another issue is the adequate distribution of the limited energy among the users. In this context multi-user systems in rural Spain are mentioned, and the chapter contributed to the report by the Spanish team reports that an electronic device that individually counts, dispenses and limits the energy provided, has been newly developed. (Since then this device has been developed further, see more in chapters 2.1.2 and 2.1.3 below.)

The following recommendations given by the report are worth to note.

On social aspects:

- *The industry should further develop cheap meters and load-control equipment for multi-user SAPV or hybrid systems*
- *Program designers should implement technological, economic and social instruments to promote optimal load balancing over the day and over the week.*

On technological aspects:

- *The industry should design components so that modularity of systems becomes straightforward, in order to allow easy expansion and reduce the initial investment cost.*
- *The industry should further develop remote monitoring systems, because these promise reductions in the maintenance costs.*
- *System designers should pursue optimal matching between PV and generator, which needs proper engineering.*
- *Industry should develop cheap individual metering systems.*
- *Industry should develop better controllers and user interfaces to reduce operational complexity.*

Task 11 – PV hybrid systems within mini-grids

Recently a new task has been added to the PVPS-programme. Approved in October 2005, Task 11 builds on the work on PV hybrid systems undertaken in the completed Task 3, and will focus on the operation of PV within mini-grids. Mini-grids are defined within the task as the interconnection of small, modular generation sources to low voltage AC-distribution systems. The source of power may be a combination of PV, wind, micro-hydro, fossil fuel gen sets and other sources. The grid typically supplies multiple users and may be interconnected with the distribution grid of the local electric utility.

In the program presentation of Task 11 the following objectives are stated:

- To define concepts for sustainable PV hybrid mini-grids taking into account local factors (specificity of the application, financing regimes, location, others);

- To provide recommendations on individual designs (mix of technologies, architecture, size, performances, other) in order to achieve high penetration level of PV as a mean to improve quality, reliability and economics of electrification systems such as mini-grids;
- To asses the potential of technologies to be mixed with PV for hybridization;
- To compile and disseminate best-practices on PV hybrid power systems.

The first Task-meeting was held in May 2006.

### 2.1.2 Recent mini-grid experiences

Traditional stand-alone PV-systems around the world are designed as single-generator, single-user systems. They are not very easily expandable. For one, there has been a technical limitation due to parallel operation of inverters being possible only through the so-called "master-slave" operation. One "master" inverter is needed to provide the frequency, while the second, the "slave", follows this frequency. [5].

An EU-funded project called "Mini-Grid Kit", completed in 2003, had the objective to design an expandable, low cost but standard quality mini-grid kit with multiple renewable and non renewable energy power generators [6].

The project has identified two modular hybrid system architectures in a power range up to 30 kW:

- The centralized DC-bus system TApS-Centralita from the company Trama Tecnoambiental S.L.
- The distributed AC-bus system Sunny Island and Sunny Boy family from the company SMA Regelsysteme GmbH.

According to the presented project results, comparison of the two concepts for several load profiles and solar fractions has shown that both system types have their advantages:

- The centralized DC-architecture is preferable in a situation of high solar fractions (e.g. PV/battery-systems) and evening loads
- The AC-based system on the other hand proved to be the more efficient solution in a system with smaller solar fraction and high energy use during the day.

Also, the "Mini-grid kit" project has been developing a new energy management system (abbreviated EMS), including functions for variable pricing, load and RES prediction, intelligent load control and multi-bus communication.

The issue of fair and optimized distribution of energy to the users in the grid is addressed by the integration of the so called Energy Dispenser for each household. The Energy Dispenser is a development of the device mentioned in chapter 2.1.1.

The two types of system configurations are illustrated by one case-study respectively in chapter 2.1.3.

An article in the July-August issue 2003 of Renewable Energy World [5], promotes the AC-system described above, with regards to system expandability (for a growing grid) but also because it presents a new solution to the control of the demand side. The authors of the article recognize that the limiting of power and energy to the users can be a first step towards fair distribution of power and energy, but would prefer to see full, flexible reaction of the consumers to the availability of power at any moment. This can be achieved by a new generation of inverters, according to the authors. The key word is variable frequency control.

One characteristic of the new inverters is that frequency becomes a function of output power. This, says the authors, opens up a number of new possibilities. An unlimited amount of these inverters can be operated in parallel, distributed throughout a mini-grid. The inverters distribute the power between themselves perfectly regardless of circumstances. Since the frequency in the grid is being formed out of the relation between the power production capacity and the actual load, the frequency becomes a measure of how much the capacity is being used and can therefore be used as a signal for demand side purposes as well.

The article also points out some general aspects that are important to consider when dealing with small island systems, with a high proportion of PV-power;

- Small island systems often have a load profile which requires restrictions on the amount of PV-power that is fed into the grid at times of low load and full batteries
- PV inverters have to be adapted, in terms of frequency and voltage limits, as island grids generally have wider voltage and frequency bands.
- Safety aspects, concerning unintended islanding, have to be addressed; enough short-circuit power has to be provided and high shares of inverter power.
- Multi-user systems, especially, have to be well organized in terms of contractual issues (such as those resulting from power limitations).

In addition, the article addresses the subject of sustainable operation of mini-grids, that is, models for securing proper operation and above all financing for the operation and maintenance during the whole lifetime of the system.

### 2.1.3 Case-studies involving mini-grids

#### Centralized power generation

In the IEA-PVPS Task 3 report SAPV – Lessons learned [1], a number of case-studies are presented, two of which concern what is categorised as mini-grids. One of these is a large scale hybrid system in Japan, with 750 kWp of PV, 3058 kWh of batteries and a 300 kW diesel generator, designed for a village of around 250 households. The other case-study is somewhat closer to the scale of system studied in this report, supplying power to 34 households in Korea. Again, this is a diesel-PV-hybrid system, with 60 kWp of PV, 1148 kWh of batteries and two diesel gen sets of 75 kW each. In both cases the power supply is centralised. Both systems are on a larger scale and more complex

than the type of system concerned in this report. No directly useful information can be drawn from the two examples as regards the control system and components.

The IEA-PVPS Task 9 report "Deployment of Photovoltaic Technologies in Developing Countries" [3] presents a case study on solar energy for village electrification in China.

A village with 350 inhabitants is electrified by a single photovoltaic system, connected to a small AC-mini-grid. The system relies entirely on PV with battery storage, the PV-modules first feeding electricity to the battery to keep it charged, then supplying excess power to the consumers. Installed capacity is 7,5 kWp. The system loads include lighting, televisions and radios, a washing machine and other community equipment such as communication devices and a ground satellite receiver. The project was completed in 1996.

A case study on solar-diesel hybrid electrification of four rural villages in Indonesia is presented in the IEA-PVPS Task 3 report "Managing the Quality of Stand-Alone PV Systems: Case studies" [2]. The report includes a relatively comprehensive presentation of the project. Aspects on system design and tariff design are summarized below.

Technical description of the system:

Array size:	23,5 kWp
Battery size:	480 Photowatt PWX 500 modules 240V, 1440 Ah (120 x 2 V Oldham Hawker batteries, 1440 Ah)
Diesel gen set:	SDMO 40 kVA
Charge controller type:	Ainelec charge control unit
Battery charger:	Ainelec 30 kW
Inverter:	Ainelec 30 kW

The PV-generator provides 80 % of the energy required, the remaining 20 % being added by the diesel gen set. The gen set can be used directly to supply the mini-grid in case of PV malfunction.

The PV generator charges the battery storage according to available irradiation. The inverter, powered by the battery, operates continuously and delivers electric energy with respect to the load. When demand exceeds PV-generation and battery capacity, the gen set is turned on, to be automatically switched off again as soon as the battery state of charge has either reached a sufficient level or after a programmed duration. In order to maintain reliability and improve the battery life time, the energy management system performs a full charge of the battery every three days.

In the village of Cal Pereire in Spain a centralized mini-grid has been installed to supply power to 5 houses and public lighting. [8]

Technical description of the system:

Array size:	5,4 kWp
Battery size:	1500 Ah (C100) at 48V
Diesel gen set:	5 kW
Inverter:	7,2 kW

The project has had a socio-technical approach, one of the key issues addressed being to secure fair distribution of energy. The solution is based on guaranteeing each user a minimum amount of energy EDA, Energy Deliverability Assured, on the basis of a tariff scheme, that established an EDA for each user and a plain tariff to be paid monthly for operation and maintenance according to the tariff contracted. For the load management an energy dispenser/meter is installed in each household (the TApS energy dispenser/meter). The dispenser continuously measures the power and energy consumed. The programmed tariff determines the maximum power and energy available for the user in the regular energy reserve. An algorithm, which is fed with data on battery state-of-charge from the central rack, gives incentives for load management with bonus-energy in case of full battery and penalizations in case of low battery state-of-charge.

#### Distributed power generation

There are fewer examples of mini-grids with multiple power sources, distributed in the grid. Below is one recent example.

On the Greek island of Kythnos a three-phase PV-battery system was installed in 2001, within the frame of the PV-MODE and MORE projects [4]. The system and operational experiences from this is presented in a paper published in September 2003 by ISET e.V., Germany [7]. The system provides electric power to 12 houses connected on a single phase 230 Vac grid. There are 5 PV generators distributed in the grid, connected via standard grid-tie inverters, and a single battery (60 V, 52 kWh) for storage, through 3 bi-directional battery inverters operating in parallel. A 9 kVA diesel gen set makes out a back-up source. The diesel gen set, the battery and battery inverters, and the data logging equipment are located in a central power house.

One of the main challenges in this project was to control a micro-grid with distributed PV generators, and the chosen solution is described by the authors like this:

- The battery inverter is able to vary the grid frequency in order to easily provide control information to the PV inverters and to the user load controllers.
- Based on grid frequency value, the PV inverters are able to continuously de-rate their power output, in order to avoid overcharging the battery.
- Frequency controlled load controllers have been installed for every household, to protect the battery from deep discharge.
- [...] grid frequency variation is applied for organizing the primary control of the grid. The battery inverters are synchronized among each other and with the diesel gen set applying frequency and voltage drops. This concept

allows to provide high peak power e.g. to start motors and enough short circuit currents for releasing circuit breakers. The peak power is shared between all running battery inverters and the gen set without additional communication requirements. The frequency window extends from 40 Hz to 52 Hz allowing for operation of usual consumers.

The authors of the paper states that the integration of distributed AC-coupled PV in a small hybrid mini-grid can be considered as a mature technology today.

## 2.2 Relevant experiences - Sweden

### 2.2.1 Installations

A review of published reports and internet search regarding installations in Sweden has not revealed any relevant information on the interconnection of single households into a mini-grid. No discussions, e.g. in internet forums, have been found concerning the subject of connecting single, PV power sources in order to distribute and make use of excess power.

There are reports on installations where the distance between the PV power production and the user is rather long, for example on Bullerö Island in the Stockholm archipelago. In such cases a higher voltage may be necessary in order to keep the cable area down over the longer distance. 48 V was chosen for the Bullerö installation. Other than that the experiences from stand-alone systems in Sweden, which all involve only one power consumer, does not present any relevant information for the mini-grid context studied in this project.

### 2.2.2 Components

Below, a number of conditions are listed, that are considered desirable for a solar powered mini-grid system in this study. The list makes out the starting point for the review of suitable components.

- Before any power is supplied to the grid from a household with PV power production, the household's own energy demand is to be met. That is, the grid is to be used only for excess power which cannot be made useful in one household, i.e. when its' battery is full and production is higher than demand at the specific household.
- Batteries must never supply energy to the grid (unless the battery is part of a central, jointly owned power unit). This is to prevent other consumers in the grid to empty the battery of somebody else's installation.
- The power extracted from the grid should be subject to an electric current limitation. Such a current restriction is necessary from a safety point of view in order to avoid higher currents than the equipment is laid out for, and also to prevent faulty installations to use up excess power from the grid. In addition, from a psychological point of view it is desirable to ascertain that no consumer can "over-use" the system. One way (though not a complete solution) to manage a fair use of the power available, is to give no household

access to higher grid amperage than its' own PV-plant can feed into the grid. For cost-effectiveness and flexibility (i.e. easy addition of extra PV-modules), the limitation device should be possible to set in steps of for example 10, 20 30 etc. ampere.

- A 12-Volt system for the consumers rather than 230/400-Volt system is considered preferable. The idea is that this will promote the choice of energy efficient equipment and prevent equipment with unnecessarily high power consumption from being installed (a case in point being old refrigerators).
- The possibility to easily connect additional power sources to the mini-grid is considered valuable. It may concern the addition of, for example, more PV-panels to the installation of one household. But, the grid also opens up for the possibility of adding a larger common power production unit, which can be placed in optimal conditions for additional PV-panels, a wind-generator, diesel or other.

Ideally, each household with its PV- and battery installation would be connected to the grid via a regulator equipped with a current restriction and with a shunt, handling 19 – 24 V in from the grid (alternatively 230 V) and 12 V out to battery backup and consumers. The purpose of the shunt is to connect the power source to the grid when excess power is being produced. The function is described in more detail in chapter 3. Such a combination is not commercially available today.

Most of the desired functions are available in some form on the market, however not in the desired combination:

- Regulators exist that are designed for 24 V in and intended for the charging of 12 V-batteries, but they do not include an amperage restriction or redirection possibilities of excess power. An earlier regulator model marketed by NAPS Power Systems did include a shunt-function for excess current, but this model has been taken out of production.
- Equipment that distributes electric current to different prioritized consumers, so called charge-distributors, exist for marine use, e.g. for start-up batteries and operation batteries. They are, however, not adapted to redirecting the current before DC/DC-inversion 24 V to 12 V.
- Equipment that enables power use from several different power sources connected in parallel (e.g. PV, wind, diesel gen sets, batteries) are supplied by several manufacturers, for use on larger sailing boats and yachts or larger land-based systems. The marketed equipment is consistently designed for single stand alone installations with 12 V or (more often) 230 V consumers. In other words, the equipment on the market do not handle distribution of power to distributed groups of consumers, whose demand are to be prioritized differently. (In the studied case, the producer's own consumption demand should be satisfied before power is distributed to others in the grid.)
- Devices exist that restrict the electric current in a connection to, for example, the national grid of 230 V. However the restriction is not adjustable and is normally dependant on some form of isolation transformer (saturation of the iron core).

A limitation is also found to be that some of the 12/24 V equipment (regulators, inverters) on the market use semi-conductors that are laid out for a maximum voltage of 36 V. The voltage from a 24 V PV-panel may exceed 50 V when not connected to a load (Voc).

## 3 Presentation of the mini-grid system

This chapter presents the general idea of the mini-grid system in the study. The system is outlined for two chosen levels of system voltage; 24 V and 230 V. For both voltage levels principal and to some extent detailed layouts are presented for the, partly new, automatic control system needed, as discussed in section 2.2.2.

### 3.1 Concept and general strategy

A small group of off-grid houses are assumed to all have their own stand-alone PV-power installation with batteries. If these houses and their power generation plants are connected to a small power grid, any excess power generated in one plant can be fed into the grid and supply other households with power or charge other batteries.

The general strategy for this so-called mini-grid is as follows:

- Each part-owner is to have an efficient power generation installed, corresponding to his/her peak power demand
- Each part-owner is to match the battery to the PV-modules in his/her own installation
- The part-owners may always charge their batteries with current from the grid, when available
- Incoming current is to be limited to stand in proportion to the mean power of the PV-modules of each household
- The part-owners are to supply power to the grid when their battery has reached an agreed level of charge (controlled by the local control unit and by measuring the battery voltage, for example)
- A part-owner with poor irradiation conditions may put up modules on an existing common building or site
- Measuring the energy consumption drawn from the grid by each user gives increased possibilities for fair distribution. It also makes it possible to detect faulty batteries that may be using excess energy for no use. A faulty battery that is no longer rechargeable may lower the grid voltage so that the other batteries risk receiving no power at all.

#### 3.1.1 Mini-grid definition

There are different definitions of the expression "mini-grid". IEA-PVPS task 11, for example, defines a mini-grid for their purpose as 'the interconnecting of small, modular generation sources to low voltage AC-distribution systems'.

In this case study, the term mini-grid is used for a small scale power grid, which:

- is separate from the national power grid
- involves feeder cables typically in the range of up to around 400 meters
- connects buildings to the main cable by short service cables (up to max. approximately 50 meters)
- may involve a system voltage anywhere between low and extra-low.

A comparison can be made with common low voltage distribution networks in Sweden where the service cables normally don't exceed 50 meters and feeding cables normally don't exceed 500 meters. Otherwise a feeding cable of larger dimension must be chosen and a new high/low voltage transformer be installed.

In this study, primarily the private initiative is treated. The starting point is that a group of home owners want to invest in a communal power grid together. Preferably, the owners should be able to also manage the grid themselves. However, in Sweden this is allowed only at voltages below 110 V (previously 50 V). At system voltages above 110 V, e.g. 230 V, a licensed electrician must be employed, and a power grid of this voltage may be owned only by a stable, recognised company (that has the ability to manage the grid "for an infinite future").

### 3.2 Mini-grid, variant 1. 24 V-dc distribution

Figure 3.1 below shows the system outline, including the connection of possible supplementary communal power supply.

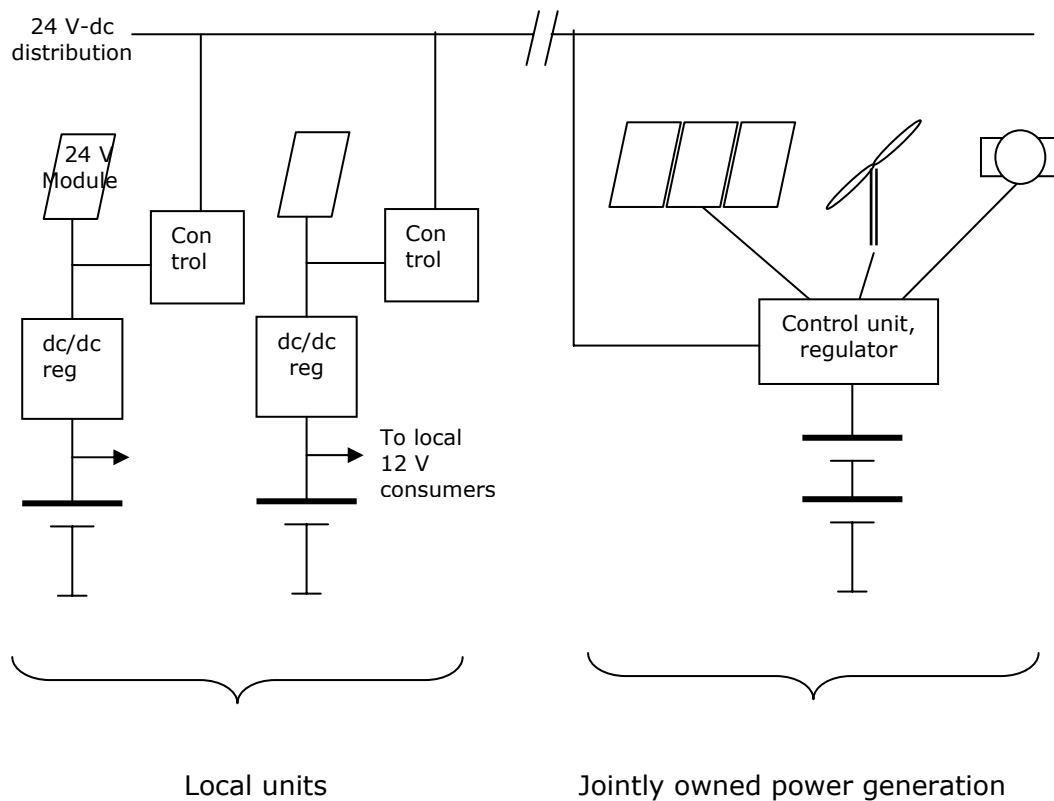
The 24 V alternative is chosen to allow somewhat higher power to be distributed than in a 12 V system, but still allowing a layman to do the installations and build the network. The Swedish regulations stipulate that a licensed installer be responsible for any voltage level above 110 V.

A 48 V system is also possible (the open circuit voltage will still be below 110 V). However, the equipment that may be chosen for a possible jointly owned power supplement, such as wind generator or diesel or petrol generator, is normally designed for 12 or 24 V system voltage.

Transferring power with 24 V over a distance soon will require very thick cables to compensate for the voltage drop. This system therefore is suited for a group of households which are situated within a rather limited area.

With a 24 V system voltage there is no need to convert the PV-generated direct current into alternating current, and such a conversion presents no advantages. The objective of the 24 V dc design is to be a solution as simple and cost-effective as possible. Note that this alternative, a multi-user grid with distributed generation in a direct current system, is a combination of which no examples have been found in the literature study (see chapter 2.1.3, Distributed power generation).

With the motivation put forward in chapter 2.2.2, internal loads at each household are 12 V. All units have 24 V modules and a regulator with dc/dc and mppt<sup>1</sup>.



**Figure 3.1. Outline for a 24 V-dc grid**

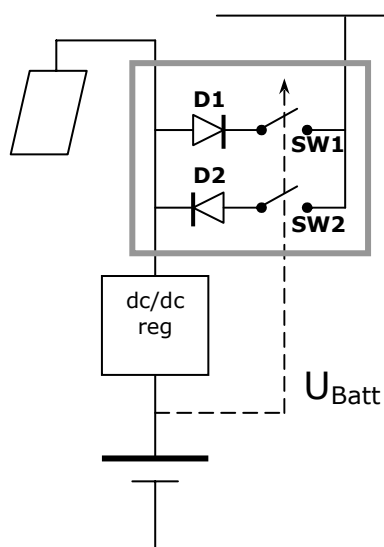
The local control unit should include the following functions:

- A function for limiting incoming current
- On-off function for outgoing amperage, that will detect the level of charge of the local battery and the local power demand
- Prevent conflict when several users are running the regulator mppt-function simultaneously
- Measuring of in- and outgoing energy

<sup>1</sup> mppt is a function that sees to that the module will always generate power at the maximum power point. If two households with mppt are connected to the grid at the same time, they will optimise the grid-voltage separately, with a resulting conflict.

### 3.2.1 Principal layout for the control unit (24 V-dc)

The figure below shows the working principle for a control unit that is responsible for connecting and disconnecting local units to the grid.



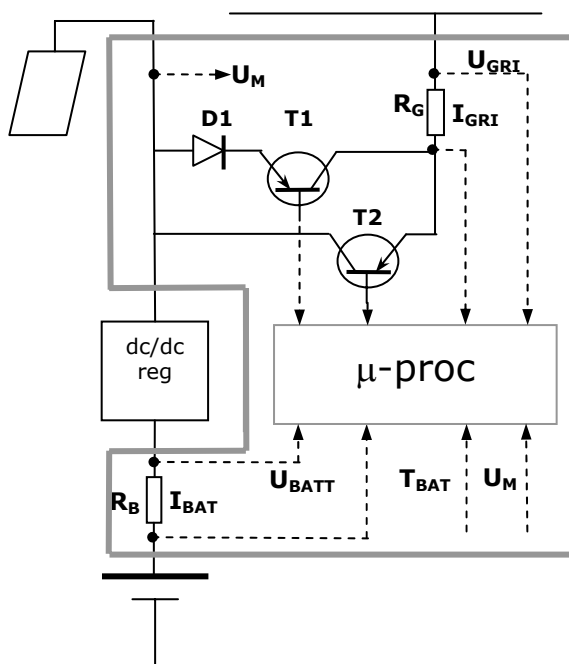
**Figure 3.2.**

When by some method it has been detected that the battery is full, the unit is to deliver energy to the grid. SW1 must shut and SW2 be open. The diode D1 prevents the PV panel of the unit to lower the grid if the modules are shaded or faulty. (D2 is not necessary.)

When the battery instead needs to be charged, the possibility to draw power from the grid should be offered. This is handled by SW2. This connection needs to be more intelligent. It means that the current in SW2 need to be controllable. The first reason for this is that it will allow a limiting function for the amperage to be introduced, which will prevent the amperage to exceed regulator maximum amperage. The second reason for current through SW2 to be controllable is the mppt-function built into the regulator. The amperage needs to remain constant over sufficiently long time periods in order not to disturb the mppt-function, which may be the case if several other units simultaneously run the mppt on connected modules.

### 3.2.2 Detailed layout for the control unit (24 V-dc case)

A more detailed layout of the control unit which is based on micro-processor control is shown in the figure below. The layout is to be seen as conceptual. It has been drawn up in order to facilitate the cost estimate and to present a solution that can handle all operation situations predicted.



**Figure 3.3**

The figure shows a possible way of implementing the control unit. The current drawn from the grid is directed from T2 by being measured across  $R_G$ . ( $R_G$  and  $R_B$  can be around 5 – 10 m $\Omega$ ).

By measuring the parameters indicated in the figure the micro processor has enough information to establish the charge level of the battery and to control ingoing amperage from the grid.

As the amperage is already being measured this value may well be accumulated and shown on a display, possibly electro mechanical.

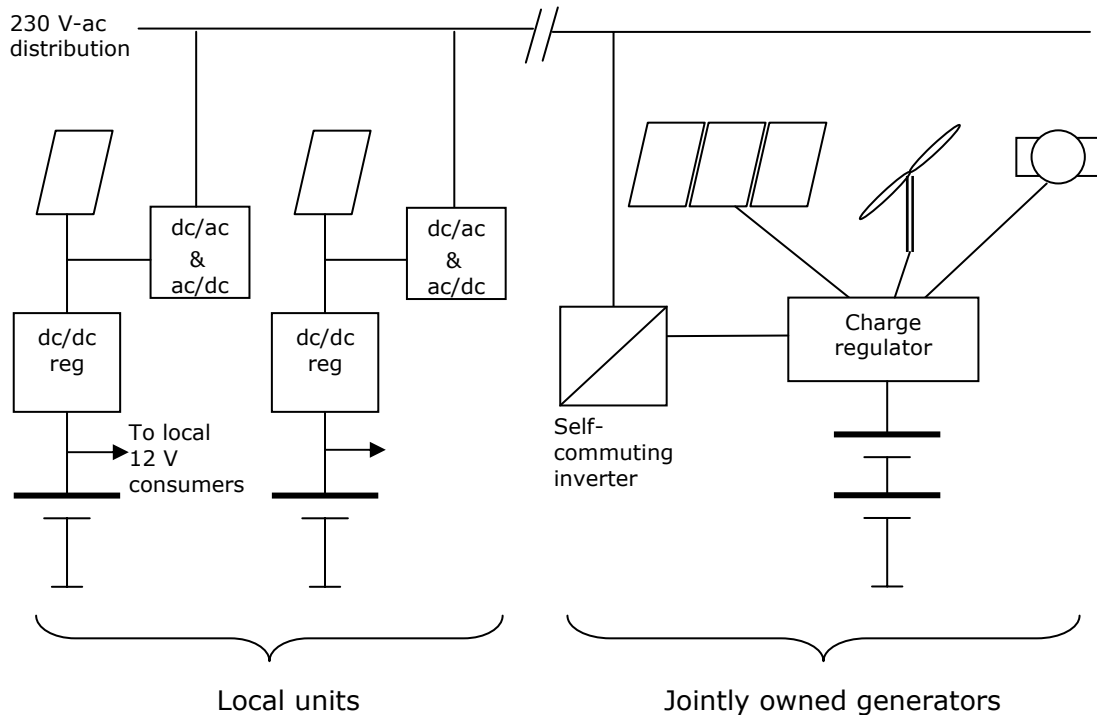
The control unit as drawn out above works also for the 230 Vac case.

### 3.3 Mini-grid, variant 2. Alternating current distribution (230 Vac)

The idea behind an AC-grid is partly that the higher system voltage makes it possible to connect a greater number of users/producers and allows larger distances, partly that it can be a preparation for connection to the national grid.

The central component in an AC-grid is a self-commuting inverter. It forms a sinusoidal alternating current with a self-generated frequency and voltage. Therefore, battery capacity must always be available, in order for the function to be maintained. Alternating current generators such as wind turbines and diesel gen sets can be made for direct synchronizing to an AC-grid. It is yet unclear whether the grid maintained by the inverter will be strong enough for other sources not to "take over". The most stable function of the grid will probably be achieved if power from wind- and diesel generators are rectified and connected directly to the common battery bank.

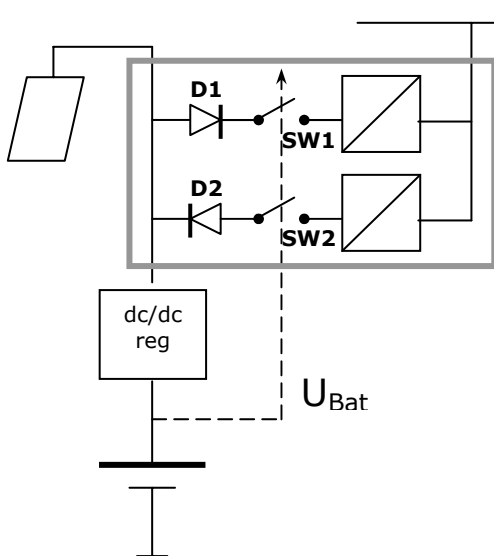
The Sunny Island inverter by the supplier SMA Regelsysteme (Germany) is especially designed to solve the above mentioned problems. It works towards a 24 V battery and is so conceived that if excess energy is at hand, the current will be rectified and charge the battery (in this case the common battery). This allows other alternating current generators to connect to the AC-side of the grid.



**Figure 3.4. Principle layout of a 230 V-ac grid.**

3.3.1 Principal layout for the control unit (230 V-ac case)

The figure below shows the working principle for a control unit that is responsible for connecting and disconnecting local units to the grid.



**Figure 3.5.**

The principle for connection and disconnection of each unit to a 230 V-ac grid. The principle follows the one drawn out in figure 3.2, but inverter and rectifier are added.

A module inverter is used for synchronizing to the grid. They are available in power levels of 100 – 200 W.

The intelligence of the micro processor (see figure 3.3) assures that optimal amperage is drawn from the rectifier on battery charging. (Diodes D1 and D2 are not necessary for the AC-grid case).

### 3.4 Costs and potential suppliers of the control system

#### **Control unit**

The complexity of the control unit that has been outlined is comparable with that of electronic controlling devices that Energibanken has earlier experience from, from other contexts. A cost of approximately 50.000 SEK for development and the 10 first prototypes is considered to be reasonable (the dc/dc-regulator excluded).

#### **Self-commuting inverter**

A unit made by German company SMA Regelsysteme is proposed. The model name is Sunny Island, SI3324, and it is assumed to manage the task. The charge regulator is built in. Cost: around €2200

<http://www2.sma.de/de/solartechnik/produkte/inselsysteme/sunny-island/index.html>

## 4 Description of the Vidinge case

### 4.1 General

Vidinge is the main island in the Vidinge-Norripada archipelago, in the northern part of the Stockholm archipelago. It borders to the outer archipelago and is situated about 8 km from Rådmansö, which is the closest mainland. Between Vidinge and mainland there is one more inhabited island. Both islands lack connection to the national power grid.

The island of Vidinge itself is about 0,5 x 1,7 km<sup>2</sup> in size. It consists of rock with rift-valleys running in north-southerly direction. Large parts of surrounding islands and skerries are natural reserve areas.

Vidinge was first mentioned in a text from the mid-sixteenth century, being referred to as a fishermen settlement. The first map of the island from 1709 includes three houses inhabited by six families in total. Today, the island has about 45 dwellings of varied age – from the later half of the eighteenth century to present time. The last permanent residents left the island in 1939 and the houses today are used predominantly for summer residency. Buildings can be found both scattered around the island and in small clusters. Most buildings are found along the old collective roads along the east and the west side of the island.

The location of the houses can be seen on the map below, Figure 4.1.

The island is connected to the telephone landline, each house connected by aerial telephone wires. The infra structure for the aerial telephone wires however can not be made useful for the power mini-grid as the routes do not match.

### 4.2 Case Study

In the north eastern corner of the island a group of about 15 houses are situated within a radius of 100 metres. This group of houses has been chosen for a case study.

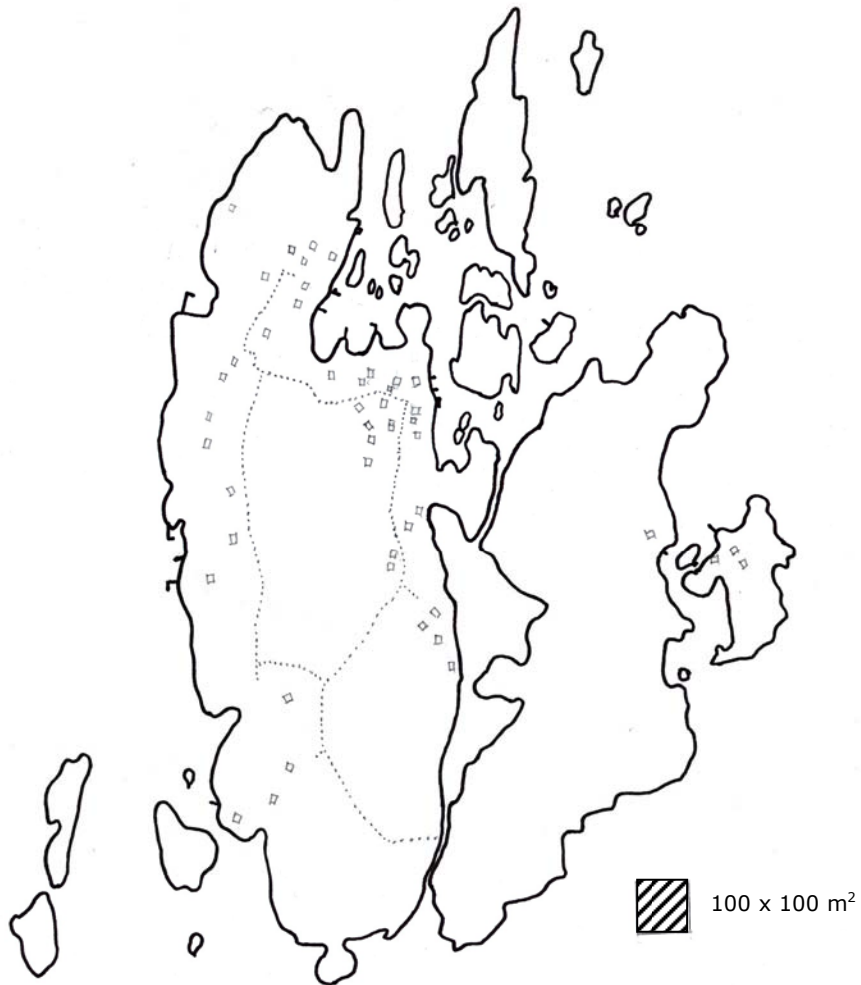
The houses can be divided into two groups of 6 + 6 dwellings. In the one group the houses are assembled in an area with radius of about 50 metres. The houses in the other group are found along a line of about 200 metres.

The obvious design of a mini-grid for these houses involves a feeder line for each of the two groups respectively and a transmission line between the groups. Each individual house would be connected to the feeder line via a service cable. Also indicated in the layout are suitable alternative connection points to the feeder cable of larger, jointly owned power generation installations, such as a larger PV-plant, wind generator or diesel gen set.

The chosen mini-grid layout can be seen in Figure 4.2.

The houses A – F make out the main example of a mini-grid of 6 houses in the case study. The houses G – M are less favourably placed relative each

other and will serve as a reference case for design and costs related to a more outstretched wiring.



**Figure 4.1. Map of the island of Vidinge with dwellings indicated.**

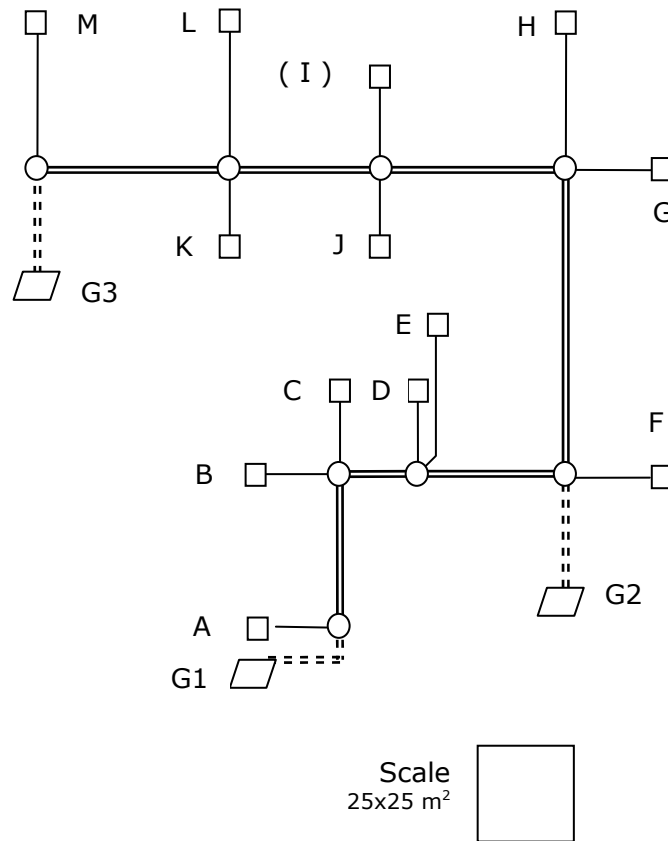


Figure 4.2. Network layout for 13 properties in Vidinge.

### 4.3 Inventory of existing equipment and desired additions

A questionnaire has been distributed to the households in the case study, to serve as an inventory of existing equipment and appliances, of desires/plans for electrical standard improvements and of the conditions for solar power generation on each property. The questionnaire results are summarised in Appendix B.

#### **Power supply equipment**

Existing equipment in the two groups of houses consist almost exclusively of some form of "standard package" PV stand-alone installation for holiday homes. In some cases such packages have been supplemented by additional PV modules or small wind turbines.

The installations have been made at three different points of time. The oldest were installed already in the mid-seventies. The next installations came about in 1990, and the newest have been installed around year 2000.

A variety of sizes are represented, from PV modules of some twenty or thirty Wp supplying a few lights, up to installations of about 200 Wp with additional wind turbine and/or diesel gen set allowing half-year or year-round utilization.

The smaller installations have not been built out because of poor solar conditions (shading), whereas several of the larger installations have been over-sized with additional PV-panels in order to compensate for that same condition.

#### **Electric appliances**

Most installations today supply power for lights, radio and TV. 10 W halogen lamps are predominantly used for lighting, but are gradually being replaced by LED-lights of 1W. Instead, utilization time for TV and radio is increasing, as is the number of appliances. Wireless telephones, mobile phones and computers are being added, leading to shortage of power, even despite built out battery banks that have been added in many cases.

#### **Desired standard improvement**

Improved electrical standard is an all-pervading desire of the households. Of highest priority in this context is the possibility to connect a compressor fridge, for continuous use through spring-summer-autumn. This is followed by a desire to use TV and computers for longer time periods. There is a demand also for building out the installations in order to have power available during a larger part of the year, however this calls for finding more suitable locations for the PV modules, as the current locations are subject to excessive shading. In one case the conditions for solar energy is too bad to be explored at all.

Typical PV installations on older and newer buildings can be seen from Figure 4.3.



**Figure 4.3. Photos from Vidinge taken at noon late December, facing north, showing PV panel mountings on elderly and newer buildings. The pictures show how panels stand out on old houses, which is considered an inconvenience by some, and that it is sometimes hard to find enough space for more panels to meet growing power demands.**

#### 4.4 Conditions for PV power production

“Standard sizing” for single homes assumes the PV panels to be placed for ideal insolation. The conditions for this are seldom achieved in real life. To guide the buyers of this kind of small size system, PV-system suppliers normally give data on expected power production, for a certain region, in the form of mean watt hours per week (Wh/w) given by the PV panel during each month of the year. Of course, the general figures supplied are indeed general, and do not apply perfectly for the location at hand. This is in addition to the fact that actual power produced of course will depend on the weather, which will always cause the production to differ somewhat from year to year. The factors combined have the result that people often become disappointed with their system, as it doesn't hold up to the promise according to their expectations.

It can be seen from the questionnaire that most buildings are shaded several hours during summer daytime, and even all day during winter. The loss of power production due to shading and non-optimal orientation and inclination angles is roughly estimated to about 50 %. The basis for this estimate is for one that several installations have been doubled in order to attain the energy generation indicated by the supplier standard sizing.

Reasons for shaded modules and for the fact that no suitable place for PV can be found on the property, are for example blocking trees that either belong to neighbouring properties and/or make out characteristic features in the landscape, or make out wind protection and provide necessary shading (cooling) of the house façade in summer. In some cases aesthetic reasons speak against larger, free standing installations on the property or to fill the wall of an older building with PV panels. Lack of insolation in winter time has to do with the fact that the majority of buildings are situated on a low level in relation to hills and forest in the south (traditionally well chosen sites with respect to weather protection). In some sites the insolation conditions are good. They are marked in the layout and used in the study.

Figure 4.4 show how trees may shade during daytime and distant hills and forest stands in the light of the low standing sun during the winter.



**Figure 4.4. Photos from Vidinge taken at noon late December facing south from some PV panel mountings.**

The pictures show both that the low standing sun does not reach over trees and rocks in the background and, with some imagination of the leafs on the trees in summer, how closer standing trees not on your own ground will shade the PV-panels. These trees, as e.g. ash trees and birches, are often characteristic objects in the environment and may not be cut down.

Values of experience for produced energy given by system suppliers (Naps, Sunwind, Exergon) have been adjusted for the weather conditions at Vidinge. The climate here is determined by the sea location. In summer it is often observed that the mainland experiences rain, whereas the sky remains clear above the islands further out. The opposite can be observed during spring and autumn. In summer, Vidinge typically experiences early morning fog until the sun has come to warm up the air. February, March and April, and October, November and December normally presents unstable weather conditions.

The table below presents assumptions for power production by a PV panel of 100 Wp, placed at optimal inclination angle and orientation and with unblocked solar insolation, for the conditions at Vidinge. The production is expressed as watt-hours per week.

**Table 4.1. Energy produced by a PV-panel of 100 Wp, [Wh/week].**

Jan	Feb	Mar	Apr	Maj	Jun	Jul	Aug	Sep	Okt	Nov	Dec
500	1500	2000	2500	2500	3000	2500	2500	1500	1300	400	400

Energy production for a PV panel of 100 Wp has been simplified to the following in the sizing calculations:

Wh/week, 100 Wp	Winter	Spring autumn	and	Summer
	400	1500		2500

## 4.5 User pattern

The owners of the selected houses were questioned about their residency times. The answers are reported in annex B: User patterns of different houses in Vidinge. From the questionnaire it was found that the usage could be split roughly into three groups; using the houses 3-4 weeks, about 2 months and 3-4 months.

As can be expected for a group of vacation homes in the archipelago, the bulk of residency times are concentrated to the summer period. A few houses stand out, being occupied from early spring to late autumn.

Many of the owners expressed expectations of prolonged residency times in a near future. The reasons for this are a mix of retirements and shared use of the house by more people.

A summary of the residency times in 12 houses are given in Table 4.2 below. The figures are presented as days per month (D/M). These figures can be compared with assumed power production by PV-panels as given in section 4.4 (Wh/week, 100W panel)

**Table 4.2. Comparison between residency times and possible PV-generation**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Staying days	7	6	10	37	72	193	187	94	24	10	15	14
PV prod	500	1500	2000	2500	2500	3000	2500	2500	1500	1300	400	400

## 5 Sizing and components

This chapter has two purposes. It gives a review of the components that will build a mini-grid and it discusses issues to be considered when sizing both PV-plant and network. Also, the mini-grid components will be sized for the different alternatives and levels of electric standard included in the cost comparison in chapter 6.

The sizing of solar power installations, single plants or mini-grids, depends on the expected power demand. The demand in turn is determined by existing and planned power consumers, and in the longer perspective on desired standard improvement. The sizing of all components of the plant/grid must take these aspects into consideration.

Today, many people consider it more or less a necessity in their holiday house not only to have a phone, full lighting in the house, radio, TV, fridge and running water, but also microwave, freezer, vacuum cleaner, washing machine and even heavier electric tools such as electrical chain saws and wood choppers. This influences the sizing and design of a stand-alone solar or wind power plant, and the necessary supplement of diesel gen sets.

Desired standard improvement in the form of added power consumers in the Vidinge case can be seen from the questionnaire, appendix B. In appendix D a detailed survey is presented of electric appliances and tools and their power demands. It includes assumptions for usage times with reference to the Vidinge case, thus giving energy demand supply values. The latter are summarized in Table 5.1.

### 5.1 Components to build a mini-grid

#### 5.1.1 The stand-alone PV power plant

**PV-modules.** Together with a battery bank the PV-modules make out the heart of the stand-alone power plant. The most common type of module is made out of some sort of crystalline silicon cells (mono-, poly- or amorphous silicon). They have experienced a dramatic reduction in price each year during a long time as efficiency and manufacturing methods have been improved; 4-5% per year over the last 20 years. This development is expected to continue. The European industry association expects to reach a price of 2 Euro/Wp in 2010.

At the same time a lot of effort is put into the development of new technologies. The most promising successor today are so called thin film solar cells, of which some variants have already made it to the market. This category of solar cell is still more expensive than the conventional crystalline cells, but the technology is believed to have a better chance to achieve cost reductions as it is being developed, mainly thanks to the manufacturing methods.

The solar cell is a current generator. The cells are mounted together in a module (which is the way they are sold) and the modules in turn can be connected in series or in parallel to achieve a desired voltage level. Common in vacation homes is a voltage level of 12 V.

**Converters dc24/dc12.** If the power is to be transferred across a larger distance or higher power is required, PV-modules of higher voltage are needed, to keep the amperage and the energy losses at bay. In the context of this case study, PV-voltage of at least 24 V should be chosen to be able to make use of the power in one house which has been produced in another. The dc/dc converter transforms the incoming power (from PV-panels or from a 24 V grid) to 12 V which is demanded by the power consumers in the house.

**Inverters dc12/ac230** may be used to transform the "household power" of 12 Vdc into 230 Vac, allowing a greater range of household appliances and electric tools to be supplied by the low-voltage, direct current source. The inverters are available with modified (square) sinus form and with pure sinus form. The modified variant is the cheaper one, but pure sinus form is required by many electronic devices such as computers, microwave ovens, electric tools with speed control. Normally, the cost of these inverters makes buying a 230 V gen set that offers higher power a better option when power demand exceeds around 1 kW.

**Batteries** Suitable batteries in this context that are commercially available for private persons are of the type lead-acid. They are available in a number of designs, such as;

- start-up batteries (e.g. car batteries) that are unsuitable in the context of solar power
- "consumer batteries", for marine and "leisure" use, which are better suited for use with solar power than the start-up batteries, however do not tolerate repeatedly deep discharging (> ca. 40 %). They must therefore be of at least double the nominal capacity required in a PV-installation
- "gel batteries" where the acid is bound in a gel. They have low self-discharge, tolerate deep discharges and have a longer life time than the above mentioned batteries. However, like "consumer batteries", the gel batteries tolerate only moderate charging amperage
- AGM-batteries, where the acid is bound in a porous material between the electrodes. They are durable (typical life time > 10 years), they are completely enclosed and maintenance-free and they have low self-discharge, tolerate deep discharge and freezing conditions. With AGM-batteries there are less restrictions on the charging since, as opposed to the cheaper batteries, they tolerate high charging amperage

The influence of the amperage restriction on charging may be exemplified by the following. For the "consumer battery" it is recommended not to exceed an amperage corresponding to the nominal capacity divided by 20; e.g. a battery of 100 Ah should not be charged with a higher amperage than  $100/20 = 5$  A. A charging amperage of 5 A used for a 100 Ah battery which has been discharged to 50 % and is of normal efficiency, will require a charging time of at least 12 hours. This is a considerable time to e.g. run a gen set to recharge.

In the case study cost comparison AGM-batteries are assumed. The cost per Ampere-hour is about the double compared to the common "consumer batteries", however the higher tolerance for deep discharge means that only half the capacity is needed, wherefore the actual cost will be roughly the same. In addition, the AGM-battery has a longer expected life time.

### 5.1.2 The network

Necessary components in order to connect single PV-power-supplied households to a mini-grid are:

- main cable
- service lines for the connection of households to the main cable
- Wiring cabinet to connect service lines to the main cable
- Ground wire with earth electrode, e.g. for lightning diversion
- Cabinet for control equipment etc. between service line and household

In addition, there may be a need for connection cables and more for common equipment such as a larger PV-plant, wind generator, diesel gen set, larger battery bank.

In the 230 V alternative there's the added need for inverters 12/230 volts.

The choice of components is made on the basis of what is commercially available, that is, what is being used in a 230/400 V heavy current grids. Components are chosen for ground laying rather than overhead lines, as this minimizes impact in the landscape and also permits the house owners themselves to handle wire laying in the extra low-voltage design (24 V). A review of the chosen components with motivations is found in appendix E.

## 5.2 Sizing of the power supply

### 5.2.1 Design values of energy-, power- and storage demands for different levels of electric standard

In this chapter the size of PV-modules, current etc, is roughly determined and discussed for a number of different levels of electric standard applied to the Vidinge case. This is done by determining the energy demand for winter, for springtime and autumn, and for summer, which is subsequently compared with the power production of a 100 Wp PV panel in ideal conditions. The sizing is made to provide input to a cost comparison.

The power generation of the 100 Wp PV panel has been adjusted from experience according to the conditions at Vidinge (see chapter 4.4), resulting in the following very rough values of power production:

Wh/w, 100W PV panel*	Winter	Spring and autumn	Summer
	400	1500	2500

\* Unit: watt-hours per week for a PV panel of 100 Wp.

From the Table 5.1 below on different levels of energy standard and use, it can be seen that;

- a minimal alternative according to "older" sizing with lighting, radio, TV and water pump, requires a PV panel of about 120 W (no shading, ideal orientation and inclination), and battery capacity of around 180 Ah (designed for five days of no sun). Lighting in the form of halogen lamps stands for around 70 % of the energy consumption.
- Alternative "Standard 1" is a minimal alternative for the Vidinge conditions, representing a simple standard but based on up-dated conditions compared to the previous case, i.e. LED lights and additional consumers. The same PV and battery capacity as in the first case is sufficient here, if computer/TV use is limited to 6 hours a day. Computer/TV in this case stands for around 80 % of total energy consumption.
- Alternative "Standard 2" is based on the conditions on Vidinge including desired standard improvements and increased use. This alternative requires PV panels of around 400 – 500 Wp, a battery capacity of around 700 Ah and a shunt of at least 60 A.

This alternative includes the addition of a small portable gen set, which is manually started only when there is a need of running vacuum cleaner, washing machine and electric tools with power demand of 1000 W or more. Energy consumption during winter may also be backed up with this gen set in combination with a simple battery charger.

- Alternative "Standard 3" represents a combined access to both 12 V and 230 V system with the possibility added of connecting high power consumers to 230 V. It resembles "Standard 2" but there is a small stationary 230V gen set which is started by remote control when there is a need of 230V or at low battery voltage. As smaller kitchen-equipment now also are run at 230V, and as the batteries also simultaneously are recharged, the PV- panel requirement is reduced to 300 – 350 W and battery capacity to app. 500 Ah.

Regarding "Standard 3" there is also a possibility to get this standard by choosing an inverter, lager battery capacity etc. but the extra cost is about the same or exceeds that of a small stationary 230 V gen set.

- Alternative "Standard 4" is a full 230 Vac standard equivalent to connecting to a main 230/400 grid. That means 3x16A 230 Vac. In this case is recommended a 3 phase 10 kVA 230 V fully automated diesel generator set combined with 3 x 2,5 kW inverters and a 24 V battery capacity of minimum 700 Ah.

**Table 5.1. Estimated PV panel and battery need for different standards of power.**

		Winter Wh/w	Spring, autumn Wh/w	Summer Wh/w	Battery, 5d covered sky, Ah,	Max current A
<b>"older" sizing, typical example</b>						
Lighting	Halogen, 8x10W, 4h/d	(2240)	(2240)	2240	133	6,6
TV/radio	40 W, 2 h/d	(560)	560	560	33	3,3
Water pump	60W, 0,5 h/d	-	210	210	13	5
TOTAL		(2800/4w)*	770	3010	180	ca 15
	PV panels	44 W*	51W	120 W		
<b>Vidinge, new sizing, simple standard, increased utilization</b>						
Lighting	LED lights, 10x1,2W, 8h/d	(670)	670	670	40	1
TV/(& radio)	Colour, digital, DVD/video 60W, 8h/d	(3370)	(3370)	3370	200	5
Water pump	60W, 15Wh/d	-	105	105	7	5
TOTAL		(4040/4w)*	775+(3370/4w)*	4145	247	Ca 11
	PV panels	64W*	110W*	165W		
<b>Vidinge, new sizing, improved standard, increased utilization</b>						
Lighting	LED lights, 10x1,2W, 8h/d	670	670	670	40	1
TV	Colour, digital, DVD/video 60W, 8h/d	(3370)	(3370)	3370	200	5
Radio	10W, 8h/d	560	560	560	33	0,8
Phone, mobile	5W, 24h/d	840	840	840	50	0,4
Computer	60W, 4h/d	- alt TV	1680	1680	100	5
Fridge	60W,100Wh/w spring, 300Wh/w summer	-	100	300	100	5
Water pump	60W, 15Wh/d	-	105	105	7	5
Microwave oven	750W, 125Wh/d	875	875	875	52	65
Coffee machine	600W, 300Wh/d	(2100)	2100	2100	125	50
TOTAL		2945+ (5170/4w)*	6930+ (3370/4w)*	10500	707	Max ca 90
	PV panels	1050W*	520W*	420W		

### 5.2.2 Sizing prior to investment

The above estimate of energy and power demand is a rough calculation carried out to find relative figures for cost comparison and to see how they varies for different levels of desired electrical standard.

When sizing a real system, a refined approach should be employed in order to determine the demand more accurately. Important factors for determining design demand are when, how often, during what lengths of time and with which intervals the house will be inhabited, but also foreseen changes in these circumstances and coming improvements in electrical standard. In the power generation estimates local circumstances such as weather conditions, shading during different periods etc. should be considered.

Proper sizing also need to assure that solar power and battery capacity match one another, so that deep battery discharge is avoided. This damages normal leisure/marine-batteries and may shorten their lifetime considerably.

### 5.2.3 Additional energy made useful by the mini-grid – for higher consumption or reduced power capacity

One benefit of the mini-grid is that a greater amount of the energy generated by the PV-systems will come to use. The most obvious example of this is that the power produced by PV-panels on houses that are not occupied, will become available for the other households.

A rough figure of how much more energy will become available to the users as a group by forming a mini-grid is given by simply looking at the user pattern for the houses. Theoretically, the power generated on a property with no demand can be used by the other households, increasing their power supply by the generated amount. Of course, if demand is not high enough and everyone's batteries are charged, all energy will not be used.

In order to make a more accurate estimate on the amount of extra energy that can be made useful by connecting a number of stand-alone plants into a mini-grid, more detailed calculations need to be performed. Jonas Hedström at Energibanken has set up an Excel-program for this purpose. The program will size up to 13 houses/plants, individually or in different mini-grid combinations, based on daily irradiation in Stockholm and a power demand of choice. In its current form it is based on user patterns according to the Vidinge conditions, which provides an example of how real residency times may vary in a group of vacation homes. Of course, it can be exchanged for other user patterns. The power demand for each house can be chosen freely. The battery charge is calculated on a daily basis and presented in a graph for each house, visualising possible over-use of the battery.

Based on the rough estimates from the preceding section for alternative "Standard 2", the required PV and battery capacity has been adjusted for each house in the case study (as the program takes into consideration the residency times over the year). The houses are then interconnected, and it has been explored by how much energy demand can be increased with unchanged PV and battery capacities. It was found that for "Standard 2", the possible total energy use in a year is increased by about 15-20 % for the groups of 6 houses, and about 30 % when both groups are interconnected.

The results are to be seen as an illustration of how large an amount of energy may be made available by the mini-grid, when interconnecting a group of off-grid self-sufficient vacation homes, with one particular user pattern. What the "energy benefit" will be for another group of houses of course depends strongly on its particular user pattern. The user pattern used in the calculations however gives a good example of a group of typical Swedish vacation homes.

The result also depends strongly on the matching of PV-capacity and batteries. A higher battery capacity in the stand alone plant will mean that the individual plant is able to make use of a greater amount of energy, thus, stand-alone plants with lower battery capacity relative PV will gain more from the mini-grid than plants with more battery storage.

In the Vidinge case, assuming the houses to be up-graded to "Standard 2", it can be concluded that the energy benefit is not of considerable importance. The mentioned figures of 15 – 30 % better use of the energy generated is to be put in relation also to the energy losses associated with the grid and converters.

Please note that the calculated energy benefit refers to a proportional increase in demand for all users, for the same user pattern. Of course, by adjusting their residency times (reducing overlaps) the users could achieve an even greater energy benefit (and correspondingly smaller, if overlap instead is increased).

### 5.3 Sizing of the cables

In this chapter the cables for the Vidinge case are sized in order to provide input for the cost comparison. As for all other equipment, the cables should be chosen with consideration to the currents that can be expected in the future, due to improved standard and increased power utilization according to chapter 4.

The cable area is chosen on basis partly of the expected current, partly of acceptable voltage and energy loss in the cable. The losses are dependant on the cable resistance, in other words the material, length and area of the cable and the current. Thus, in order to size the feeder and service cables it is necessary to know the required lengths, desired current and what may be considered acceptable voltage and energy losses.

#### 5.3.1 Acceptable losses

Acceptable voltage drop is determined by the lower limit on input voltage for the DC24V-DC12V converter. This is normally around 20 V, giving a maximum voltage drop of 4 Volts (24 – 20 V). The energy loss in the cables at 4 Volts voltage drop is approximately 30 %. When pure excess power is to be transferred from a PV-installation, this may be considered acceptable. However, as a design value the energy loss should preferably be kept below 10 – 15 %, corresponding to a voltage drop of roughly 2,5 V. If the losses are assumed to be compensated for by extra PV-power, with higher energy loss it becomes more cost-effective to increase cable area than PV area.

When several consumers are connected to the network the total energy loss will depend on the amperage and cable lengths for each consumer respectively.

### 5.3.2 Cable length required

It has been found that the cable lengths required for the groups of houses in Vidinge, provides an example that may well be representative for many groups of self-sufficient houses. See appendix F for details. For the cost analysis the following cable lengths are assumed:

- 25 metres of feeder cable per property
- 25 metres of service cable per property for the majority of properties and 40 metres for some.

### 5.3.3 Current

The current design value for each property is calculated from the effective PV demand at "improved standard" and "increased utilization". This will be the highest power that is possible for the plant of one house to distribute onto the grid, when the household in question has full batteries and no demand. If the households are being supplied from a communal PV-plant the design value in this case will be the sum of the demands of all households.

- The alternative "Standard 1" in Vidinge, has an expected PV demand of 120 – 165 Wp, for a household with low standard and limited use. Occasional winter power demand must be met by a separate gen set, because of the particular conditions for the properties where the low sun is blocked by hills and forest. The winter demand is therefore not considered in the calculations.

A feeder voltage of 24 V gives the design current of 5 – 7 A. 7 A ingoing and outgoing current is being used in alternative "Standard 1".

- Alternative "Standard 2" in Vidinge, has an expected demand of 400 Wp in summer and around 500 Wp in spring/autumn, for a household with improved standard and increased utilization. With the same reasoning as above, the occasional winter demand must be met by a separate energy supply.

A feeder voltage of 24 V gives the design current of 20 – 25 A. Moreover, this would correspond well with a jointly owned gen set of say 3 kVA for the case of 6 households in the mini-grid, or a gen set of 6 kVA for the case of 12-13 houses. The gen set would be able to supply each household with 20 A, all households connected at the same time. This may be the case in periods of prolonged lack of sun.

20 A ingoing and outgoing current is being used in alternative "Standard 2".

- Alternative "Standard 3", same as standard 2 but including consumers with high power demands, supplied by 230 V. If the 230 V voltage is being generated from 12 V by an inverter of 12/230 V, in essence there is no difference to "Standard 2". If a separate gen set is being used to generate the 230 V voltage, the PV demand is estimated to fall to 300 – 320 Wp and battery demand to 500 Ah.

A feeder voltage of 24 V gives the design current of 13 A. 13 A ingoing and outgoing current is being used in alternative "Standard 3".

#### 5.3.4 Cable dimensions

The choice of *feeder cable* size is made on basis of calculated voltage and energy losses for the distances on Vidinge. The network losses are calculated from total losses from the separate parts (resistance x current square) divided by the total supply (voltage x current).

A "worst case scenario" is used in the calculations by assuming that the total power demand is met by a communal PV plant (and perhaps added gen set). This may be an option in the real Vidinge case, due to the problems of shading for many of the properties. A PV-plant located at one of the proposed sites in the layout (Figure 4.2) would in principle double the panel efficiency compared to current real conditions. The common PV-plant(s) are assumed to be connected to the network by a feeder cable of 30 metres.

The chosen cable types and dimensions can be seen in the Table 5.2 below.

The calculations show that the network losses are acceptable even with the highest amperage (20 A). The choice of cable size is made on basis of the voltage drop. In a "worst case" the calculations show that the voltage drop with a 4x95 mm<sup>2</sup> cable borders to unacceptable, and 4x150 mm<sup>2</sup> should be chosen.

**Table 5.2. Cable material and size**

	Material	Size
Feeder cable	Aluminium	4x150 mm <sup>2</sup>
Service cable	Copper	4x10 mm <sup>2</sup> /4x16 mm <sup>2</sup>

It is found that these dimensions correspond to the dimensions used by power distribution companies as a "rule of thumb" for connection to the main grid. This means that the mini-grid will be possible to make use of even in a possible future conversion to 230 V and connection to the mainland grid.

## 6 Cost analysis

Prices and costs that are used for the comparison of different alternatives are discussed in this chapter. As can be seen, prices can vary considerably depending on factors like the buyer's possibilities to achieve discounts, possibilities to do work by yourself, authority requirements and safety and other regulations.

Quoted prices have been collected from a number of different sources, e.g. supplier catalogues on solar power units for vacation homes and for marine use; verbal information from manufacturers and installers; comparison with similar, existing installations/labour. The prices are used in order to make a relative comparison between a number of different alternatives. Some sources have expressed the wish to be anonymous, wherefore references are not presented.

In each individual case the real costs will differ depending on local conditions, on the desired standard, on length and frequency of residency, on available "package solutions" and more.

### 6.1 Network cost for the mini-grid solution

In the following sections the costs associated with equipment for the common network are treated; that is, the costs for the network in to and including the wiring cabinet for the house's internal wiring.

#### 6.1.1 24 V system

##### **Feeder and service cables**

The same cable types for feeder and service cables are used as in normal 230/400 V installations. The "rules of thumb" used by grid owners and power distributors regarding cable area requirements for different wire lengths in 230/400 V systems, has been found to correspond well to the areas needed in a 24 V system.

Since the study started, the prices of cable have risen significantly. Rises of 50 – 100 % have been experienced in a year. The reason for the increased prices is rising raw material costs for plastic, copper, and aluminium, reflecting a rapidly growing demand on the market.

Despite it being standard cables on a large market, it is problematic to establish a budget cost for the cables. There is a significant difference in prices between listed prices, different discounts and contract prices available. For the cables in the study, cable cost information has been given in a range of up to a factor of 10.

The lowest price given in the comparison is an example obtained informally from an energy company with a favourable contract. It is included only as an example, but would not be a price available to a private person generally.

In the cost comparison prices from internet suppliers have been used. Several internet suppliers have been found who offer prices of the same order of magnitude. However, they are "spot prices" and may change from one day to another.

In the future, newer types of PEX-insulated aluminium cables (CENELEC type N1XV-AI) might be cheaper than PVC-insulated with copper-mantle. For the moment (August 2006) this type of cable is not available from internet suppliers.

To the listed cable prices are to be added freight costs, and the cost for cable protection pipes and warning-tape when laid underground. The column "Cost estimation on site\*\*" includes estimated freight costs, cable protection etc. of approximately SEK 25 for weaker cables and SEK 50 for thicker cables per meter.

**Table 6.1. Prices of cables.**

Cable type	Price SEK /meter (incl. value added tax, VAT 20%)				
	wholesale recommended price	supplier *)	'internet'-supplier	Energy company w. contract	Cost estimation on site **
EKKJ 4x10+10mm <sup>2</sup>	575	250	75	45	100
EKKJ 4x16+16mm <sup>2</sup>	1100	422	125	75	150
AKKJ 4x95+29mm <sup>2</sup>	1120	571	250	180	300
AKKJ 4x150+41 mm <sup>2</sup>	1570	843	350	240	400
Earth line Cu 25 mm <sup>2</sup>	-	81	30	20	40
*) Informs that heavy discounts of more than 50% of listed prices occur					
**) Including transport, cable protection, marking tape etc.					

Very surprising is the high wholesale recommended price (i.e. the price for private persons who are not eligible for discounts).

For feeder cables the AKKJ 4x150mm<sup>2</sup>+41 mm<sup>2</sup> is chosen. Alternatively two parallel AKKJ 4x95mm<sup>2</sup> may be used, if this would be cheaper to purchase.

For service cables the EKKJ 4x10+10 is chosen for 25 meter-lengths and EKKJ 4x16+16 for 40 meter giving the same voltage drop.

### **Wiring cabinet**

This will be of the same type as used in 230/400V systems to connect service cables to houses. They are made of galvanised steel with underground parts reinforced by epoxy paint, which is proven resistant to the corrosive sea atmosphere.

A price of SEK 13 000 incl. VAT is given by suppliers of wiring cabinets made for connecting up to three service cables to a feeder line (price is subject to possible discounts). A contractor has indicated a price of SEK 7.500 incl. VAT. One internet supplier indicated 25% discount on ordinary supplier cost or around SEK 10.000, including delivery if five or more cabinets are ordered.

In the calculations a cost of SEK 10.000 is used for this equipment, installed and ready on site.

### **Cabinet for the house wiring**

A cabinet for the connection of service cable to the house wiring is estimated to SEK 1000.

### **Cable laying, installation**

In the 24 V system the cable laying and all connections are assumed to be handled by the house-owners themselves.

#### **6.1.2 230/400 V system**

A recurring question is whether 230 V system voltage would not be preferable in order to reduce cable dimensions (and costs), network losses and voltage drops across larger distances. In Vidinge this could be interesting for the case with 12 houses in a mini-grid extending across approximately 400 metres.

According to power distributors the cable areas in a 230 V system will be approximately the same as in the 24 V case. If 230 V system voltage is chosen, cables etc must be sized to permit a possible future connection to the national grid. This is not up to the house owners to decide on; see more below on network concessions. Cable costs will therefore remain the same for both 24 V and 230 V systems.

With a 230/400 V system, certified installers are required. The laying (excavation and refilling) and connection of service lines can be estimated to around SEK 20.000 incl. VAT per household.

The laying (excavation and refilling) and connection of feeder cable is estimated to around SEK 150.000 incl. VAT per kilometre. The cost for feeder cable laying in a mini-grid of close to 400 m (12-13 houses) will thus amount to around SEK 60.000. Due to rocky ground conditions, the cost will be raised by approximately 100% to around SEK 120.000.

230/400 V system voltage also brings other consequences. For example, any cable laid out between properties is subject to the network concession regulation. With few exceptions this will mean that a power or network company will be involved. In addition, an official survey will be required for the cable laying, which at a rough estimate will cost SEK 15.000 – 20.000 per property, adding up to SEK 180.000 – 240.000 for 12 properties.

The total *network* cost for a mini-grid with a system voltage of 230 V thus may exceed SEK 50.000 per household, under existing regulations.

#### **6.1.3 Overview 24V, 230V system**

In Table 6.2 an overview of the network costs associated with different mini-grid designs is presented. The network includes 30 metres of cable to a common site for PV-modules and another 20 meters of cable to cover approximately 5 meters of bending and coupling ends for each wire cabinet (four per group of households). See appendix F.

Considering that essentially the same cable areas and lengths are required for the 230 V system as for a 24 V system, the 230 V solution disqualifies due to the higher laying costs, authority requirements etc., for a mini-grid involving more than one property.

**Table 6.2. Total network costs – mini-grid 24 V and 230 V. Labour is assumed to be carried out by the house owners themselves in the 24 V case.**

Network cost SEK	Minigrid 24V 6 house A – F, ca 130 +20 m*	Minigrid 24V 6 house G – M, ca 180+20 m*	Minigrid 24V 12 house A – M ca 390+40 m*	Minigrid 230V 12 house A – M
Feeder cable	60.000	80.000	172.000	172.000
Service cables	18.500	25.500	44.000	44.000
Wiring cabinets	40.000	40.000	80.000	80.000
Grounding equip.	8.000	8.000	19.000	19.000
Cabinet for house wiring	6.000	6.000	12.000	12.000
Laying; Feeder cable, service cable	By house owners	By house owners	By house owners	96.000 240.000
Permits etc				200.000
Sum	132.500	159.500	327.000	863.000
Mean net cost /house, SEK	22.100	26.600	27.300	71.900
*) app. 2x2,5 m coupling ends per wiring cabinet				

## 6.2 Cost of power supply

This section concerns the costs of a stand-alone solution and the possible additional cost for connection to a mini-grid of 24 V system voltage or 230 V system voltage, or connection to the mainland grid.

Even if all PV-modules or other power supply is placed in one spot instead of being evenly distributed among the houses, in the comparison they are assumed to belong to the houses respectively.

The power installation includes PV-modules, regulator, batteries, battery charger, installation material and possibly supplementary petrol/diesel gen set or wind turbine.

### PV-panel

PV supplier information indicates a cost of SEK 5000 incl. VAT per 100 Wp. The installation is assumed to be carried out by the house owners themselves.

### Regulators and control equipment

Stand alone regulators:

A regulator for the alternative "Standard 1" has a cost of just below SEK 1000, including voltage protection.

A regulator for the alternatives "Standard 2" and "Standard 3" including a shunt that can handle an additional 65 A from the battery, would cost around SEK 3.000.

Grid control:

At the connection of the household to the grid, functions are required for incoming amperage limitation and for redirecting excess PV-power to the grid, when the battery is fully charged. The cost, including cost of development, is

roughly estimated to around SEK 50.000 for 10 devices (e.g. for a demo installation). The cost can be expected to be dramatically reduced in volume production.

Since most regulators in the existing installations in the Vidinge case do not hold up to the requirements on built out electrical standard and increased utilization, the existing regulators need to be exchanged for new ones. The most cost-effective and simple solution would be to have a device that included all the above functions, however this is not available on the market today.

For the cost estimate in the study a cost of SEK 5.000 per unit for new-developed regulators is being used (to be added to the cost of the stand-alone regulator, see chapter 3.4).

### **Batteries**

In the calculations the cost for AGM-batteries including connection cables etc. is assumed to be SEK 3.000 per 100 Ah, 12 V, including VAT. Correspondingly, for 24 V SEK 6.000 is assumed for 100 Ah.

### **Diesel/petrol generators**

The cost for a transportable gen set of 2,5 kW, to use for occasional high power consumers and for a battery charger for occasional battery charge support, varies between SEK 4.000 and 10.000. In the cost estimate here a cost of SEK 6.000 is assumed.

The cost of a stationary 2,5-3 kW gen set for alternative "Standard 3" with remote control is around SEK 20.000 in petrol design and 30.000 designed for diesel.

The cost of a stationary 6-8 kW gen set for alternative "Standard 4", fully automated, is around SEK 70.000. (This cost does not include the battery bank of about 700 Ah/24 V or the inverter/charger 3x2 kVA.)

### **Charger, inverter**

A battery charger of 230V/12V 20A for supplementary battery charge by the gen set in Standard 2 costs around SEK 3.000.

For alternative "Standard 3" an inverter 12Vdc/230Vac may be used instead of a stationary remote-controlled gen set. An inverter with continuous power of 1,6 kW costs around SEK 10.000. However, together with the need of more PV-modules and batteries, comparable to "Standard 2", the cost will be higher than with the gen set solution.

For alternative "Standard 4" an inverter for 24V/230V with a continuous power of 2,5 kW and with simultaneous charging function from the connected gen set costs around SEK 20.000 (see chapter 3.4). As the diesel gen set of 6-8 kVA is expected with 3-phase 230V, three such inverters are needed for the alternative "Standard 4", amounting to a total cost of SEK 60.000.

### **House installation**

*24 V extra low-voltage.* In the 24 V system ("Standard 1" and "Standard 2") the installation is assumed to be carried out entirely by the house owners themselves. The cost for material is assumed to differ marginally between

different electrical standards, whereas however appliances and operating times do differ. SEK 2.000 is assumed as a standard cost for installation material for each household.

*24 V extra low-voltage, 230 V occasional use.* In the 24 V + 230 V system ("Standard 3") it is assumed that the 230 V power point is not a fixed installation, thus no cost is added for this.

*230 V stationary.* In the 230 V system with fixed installation ("Standard 4") reasons of responsibilities and safety call for other types of installation equipment and the installation must be carried out by a certified electrician. Roughly, SEK 1.000 can be assumed per connection point (i.e. power points in the house, switches, etc.). For the central fuse box can be assumed a cost of SEK 4.000. With a low assumption of 10 power points in the house and 5 power switches, completed with an assumption for travel expenses to the island, a cost for installation is assumed to be SEK 20.000. (Confirmed by verbal information from an installer of about SEK 15.000 – 25.000.)

**Table 6.3 Cost of the installation for one household, for different electrical standards.**

Cost per household SEK	Standard 1 12 V simple	Standard 2 12 V extended	Standard 3 12 + 230V	Standard 4 230V, 3x10A permanent inst.
PV modules	6.000	20.000	17.000	-
Regulator etc	1.000	3.000	3.000	-
Batteries	6.000	21.000	15.000	42.000
Installation	2.000	2.000	2.000	20.000
Inverter/charger	-	3.000	3.000	3x20.000
Gen set	-	6.000	20.000	70.000
Total cost per house	15.000	55.000	60.000	192.000*)

\*) For the alternative of connecting to the mainland grid via sea cable see below.

### Connection to mainland high voltage grid

Connection of a 230/400 V installation to the mainland grid via a 12 kV sea cable and transformer can be compared to "Standard 4". This connection is made by the company who has the network concession in the area. A recent quotation indicates a cable price SEK 100.000 per kilometre incl. VAT. To this is to be added the costs for a transformer with cabinet, for switches, etc. (approximately SEK 100.000) and for land cable (approximately SEK 200.000 per km, underground).

The distance to the mainland connection point is around 9 kilometres. Another one kilometre land cable is needed in total, to connect to the grid in both ends.

**Table 6.4. Rough cost estimate of 230V installation connected to mainland**

	SEK
Sea cable 12kV, 9km	9x100.000
Land cable	200.000
Transf. etc	100.000
230VGrid = 230Vminigrd 12 houses	863.000
230V installation 12 houses	12x20.000
Sum 12 houses	2.303.000
Mean value/house	192.000

This is in accordance with an informal cost estimation of MSEK 2 – 2.5 obtained by verbal information from a power supplier, excluding installations in the houses (approximately SEK 200.000 per connection).

The calculations show that if all 12 (or more) households in the case study are sharing the cost of a permanent 230/400V installation connected to a main grid, this cost will be about the same as for each household to install a stand-alone 230V stationary 6-8 kVA gen set with battery and inverter backup.

### 6.2.1 Special conditions in the Vidinge case

The real conditions in Vidinge correspond poorly to the assumed general conditions, mainly due to poor siting possibilities, the difficulty to avoid shading and to place the PV-modules optimally. The Vidinge case presents an example of a situation, where the households could benefit from the mini-grid by the increased freedom of placing the PV modules. Below, the economic benefit of this is explored for the Vidinge case.

Table 6.5 gives an overview of the present, real conditions of shading at Vidinge. This is translated into a rough added cost for the households, who are over-sizing their installations in order to compensate for the lost energy.

**Table 6.5. Costs associated with over-sized PV-installations due to poor insolation conditions. "Standard 2", houses A-F and G-M.**

	House A	House B	House C	House D	House E	House F
Shading	50%	50%	80%	50%	totalt	0%
Added PV demand or other	+ 100%	+ 100%	Gen set, battery bank	+ 100%	Gen set, battery bank	0
Extra cost implied	+20.000	+20.000	+25.000	+20.000	+25.000	0
Total cost houses A-F	SEK 110.000					
Comparative cost per house for mini-grid 6 houses A - F	SEK 18.300			% 55		

	House G	House H	House J	House K	House L	House M
Shading	0	25%	25%	50%	50%	0%
Added PV demand or other		+50%	+ 50%	+ 100%	+100%	
Extra cost implied		+10.000	+10.000	+20.000	+20.000	
Total cost houses G-M	SEK 60.000					
Comparative cost per house for mini-grid 6 houses G - M	SEK 10.000			% 25		

The costs cover only material. All mounting and connection is expected to be carried out by the house owners themselves.

**Table 6.6. Costs associated with over-sized PV-installations due to poor insolation conditions. Houses A-M, "Standard 2".**

Sum, houses A-M	SEK 170.000
Mean extra cost per house (A-M)	SEK 14.200

A similar calculation (not shown) of "Standard 1" gives the mean values per house in table 6.3.4 below.

**Table 6.7. Costs associated with over-sized PV-installations due to poor irradiation conditions. "Standard 1".**

Extra cost mean value A-F	SEK 6.300
Extra cost mean value G-M	SEK 3.000
Extra cost mean value A-M	SEK 4.700

The savings that the households could achieve in the Vidinge case due to better location of PV-modules are to be compared with the added costs of the network and connections to the mini-grid. The net saving or cost calculation for "Standard 2" is shown in Table 6.8 below.

**Table 6.8. Comparison of costs and savings with the mini-grid solution in the Vidinge case. "Standard 2".**

Cost/Saving SEK	Minigrid 24V 6 house A – F,	Minigrid 24V 6 house G – M,	Minigrid 24V 12 house A – M	Minigrid 230V 12 house A – M
Network cost	123.000	155.500	283.000	817.000
Regulators, extra cost	12.000	12.000	24.000	24.000
Total cost minigrid	135.000	167.500	307.000	841.000
Comparable cost stand alone (tab.6:5)	110.000	60.000	170.000	170.000
Net saving	- 25.000	-107.500	-137.000	-671.000
Mean net saving*) /house, SEK	-4.200	-17.900	-11.400	-55.900

\*) Compared to over sizing panels according to table 6:5. Negative saving = cost

Note: Cable prices have risen app. 100% during a year. With half the cable price there would have been a saving with a 24V minigrid.

### 6.3 Cost comparison

Below, the costs per "average house" are shown in a table.

The "mini-grid cost" per house is the sum of the individual stand-alone solution cost, the network cost and an added cost for the required "mini-grid regulator".

Cost figures are rounded off up to even SEK 1000.

**Table 6.9.**

Costs SEK, per "average house"	Electrical standard			
	1	2	3	4
Alternative				
General calculation Single PV-plant, gen set etc	15.000	55.000	60.000	192.000 (gen set + battery bank)
Case Study Vidinge Single PV-plant, gen set etc	20.000 (± 2.000)	69.000 (± 4.000)	74.000	192.000
Minigrid 24V house A-F	42.000	82.000	87.000	
Minigrid 24V house G-M	47.000	87.000	92.000	
Minigrid 24V 12 houses	47.000	87.000	92.000	
Minigrid 230V 12 houses			137.000	
Connection to mainland power				192.000

Note: Cost in minigrid 24V 12 houses is not the mean value of A-F and G-M as the cost of the connection cable is added, giving a value similar to the more expensive G-M case.

A comparison of the different alternatives for "Standard 2" (which represents the desired standard for the majority of households in the case study) shows that choosing a mini-grid solution instead of stand-alone solution will add about SEK 10.000 for each household. Largely, the added cost is made out of costs for feeder and service cables. As have been noted in chapter 6.1 it is difficult to find the correct price for cables. The costs of cables have increased by up to 100 % in the last year – which translates to about the calculated added cost of the mini-grid.

## 7 User behaviour

Arguments have been put forward in opposition to building communal mini-grids, putting the difficulties associated with communal property in focus. A mini-grid would involve a number of households that jointly own the network and perhaps one or more power supply units. The responsibilities and benefits associated with the jointly owned equipment need to be shared in a way that satisfies all part-owners.

Some of the critical arguments are

- An individual user may, purposely or unawares, over-use the system for example by adding consumers with higher power demand than acceptable. This may be difficult for the other part-owners to detect and prove.
- Difficulties may arise regarding the fair distribution between the users of labour and of costs for maintenance and reinvestments.
- Jealousy may arise amongst the users because of unfair distribution of costs and advantages associated, or mere suspicion that this is the case. It is not uncommon that this spreads a negative atmosphere in the neighbourhood.
- Future altered conditions (e.g. change of house owner) may put the original agreements, designs, arrangements etc. in question.

These phenomena are well known from other areas, like private roads, communal water and sewage installations, irrigation plants and ditching undertakings.

In Sweden, there are well established formal ways to handle conflicts of interest by the formation of formal communal plants, cooperative management associations and easements to use land of another's property. These issues are handled by the surveying office. This way to handle the cooperation is however costly and its' value is questioned in the mini-grid context of this study.

Nonetheless, through a great variety of association activities there is also a well established acceptance among the Swedish people for cooperation in matters that benefit the group, and for the associated need to adhere to certain rules in order to make the cooperation work. It is not uncommon for neighbours to work together on issues that are of mutual interest. It is believed that a group of up to 5-6 neighbouring households normally would be able to handle an economic cooperation without the differences in opinion risking to become too hard to handle for the group.

The idea of the mini-grid is to interconnect households that all have a clear benefit of doing so. This of course is a critical factor for a successful co-operation. As have been discussed in previous chapters, there may be different benefits to motivate a mini-grid;

- A household may lack suitable sites for PV

- A more favourable site may be made available for the PV-modules with regards to insolation conditions or aesthetics
- The houses may be used during somewhat different time slots in the year, thus making it advantageous for all or some to have access to the PV-capacity of the others when the residency time does not overlap
- Sharing the investment cost of an added power source is made possible (e.g. a wind turbine)

Typically, the type of motivation for building a mini-grid will most probably differ among the potential part-owners. It will be crucial to make a clear agreement on how the costs, benefits, labour and other are to be shared and managed.

As long as only excess power is put in to the grid, that is, when the own demand is already covered and the own battery is fully charged, no one can over-use the power supply of another. In order to avoid that someone installs an oversized battery and uses more of the communal excess supply than he/she is offering through own PV-capacity, the current from the grid should be limited to correspond to the installed power capacity of each household. The battery bank must also be matched to the PV supply of each part-owner in the grid. Lastly, measuring the energy put in and drawn from the grid by each owner assures that faulty components be detected and corrected and makes it possible to control the fair distribution of costs and benefits in detail.

## 8 Discussion and conclusion

There are many possible reasons for individual households with off-grid solar power supply to interconnect their power plants and co-operate in a so-called mini-grid. The reasons may vary from purely aesthetical to economical.

An inventory of the conditions in a real case of 6 or 12 properties on the non-electrified island of Vidinge in the Stockholm archipelago shows that this is indeed the case.

The desired electrical standard in the studied case has been found to include, at least, power for lighting, telephone, water pump, fridge and relatively lengthy use of TV, computer and radio. To meet these demands in the studied case, which concerns an island situated about 8 km from mainland, off-grid power has been shown to be more economical than connecting to the mainland power grid. The most economical option is a power supply solution that combines PV-power, batteries and a "back-up" gen set.

In the comparison between individual off-grid power solutions and an interconnection into a mini-grid, the costs of cables are of great importance. The substantial rise in prices on power cables, due to increased prices on copper and aluminium on the world market, in fact has erased the economic benefit that a mini-grid in the case study might have given only a year ago (assuming all labour to be carried out by the house owners). It's interesting to note that the price a private person pays for cables may be as much as ten times the price to which the local power company may acquire them. Employing a company to do the cable laying because they have access to lower cable prices will however raise the total cost due to the cost of labour.

But the expected cost reductions of PV also work in favour of the individual solution, in terms of investment cost.

Other benefits have been underlined by the Vidinge case. The situation in the real case shows with clarity how difficult it may be for a house-owner to find an optimal placing of PV-modules. It has been found that the possibility to find better sites for PV-installations and to share the investment cost of a built out power supply with others, is highly valued. These are the reasons that would motivate a mini-grid, rather than the energy benefit.

An aesthetical benefit of the mini-grid is that the impact of the solar panels in the old cultural landscape can be minimized, as a bigger choice of possible sites is made available. Instead of covering the walls or roofs of older buildings or cutting down trees that are an essential part of the landscape, the panels may be placed in a better place, perhaps in between two properties.

Especially for properties where solar power previously has not been an option, the mini-grid would introduce a benefit by offering the choice of investing in PV. The case study shows that this is generally preferred, above using a gen set for the power supply. Any reduction in the use of petrol/diesel gen sets is considered an improvement for the local environment.

An impediment is that suitable regulators or other electronic equipment for connecting individual off-grid homes into a mini-grid are missing on the market, even though the necessary functions are or have been available separately in other contexts.

A possible obstruction is presented by the present Swedish electricity distribution regulations which go against communal power solutions by demanding a network concession for any cable laying across the border of a property.

The conclusion is that although the case study does not prove any direct economical benefits for a group of off-grid households to join in a mini-grid, it is shown that there are other advantages that in some cases may motivate such a collaboration.

It should be possible for the house owners themselves to build the mini-grid (e.g. for cost reasons). In order to do that however, real experience needs to be collected through a demonstration project.

Some functions that are needed for the intended operation of the mini-grid have been identified to be missing in the controlling equipment available in the market. The simplest solution to use would be a new type of regulator where two new functions would be integrated; amperage limitation and redirection of excess power. Such a device is found to be motivated in other contexts also.

There is a need to clarify and possibly modify the current regulations in order to make it possible to place small scale power supply units outside the own property and to facilitate joint ownership and the exchange of power across property borders, in the small scale.

It would be of interest to install a mini-grid for demonstration purposes, in order to further explore the practical and technical implications and solutions. This type of collaboration between neighbours, in vacation home areas but also among permanent residents in remote locations, is believed to become of growing interest in the future as the cost of main grid power supply increases and the alternatives become more available.

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## Appendix A. Inventory of the houses at Vidinge

House	House type	Construction year	Area m <sup>2</sup>	Heating	Kitchen	Lights, power demand and supply *)
A	Simple bungalow	ca 1965	25 10	Paraffin oil heater	Calor gas-stove, -fridge	6 lights PV
B	Simple bungalow	ca 1965	24	Firewood heater	Calor gas-stove, wood stove	8 lights PV
C	Simple bungalow	1974/2000	35	Firewood heater	Calor gas-stove, electric fridge	Paraffin oil lamps Fridge, TV. PV
D	1½-storey semi-detached house, timber	1873	60	Firewood heater, gas heater	Calor gas-stove	9 lights PV
E	1½-storey semi-detached house, timber	1873	50	Firewood heater	Calor gas-stove	2 lights, TV, Transporting charged batteries from mainland
F	Simple bungalow	ca 1945	25	Firewood heater, gas heater	Calor gas-stove	4 lights, TV PV
G	1½-storey house, timber Single storey house, timber	ca 1850 ca 1850	60 30	Firewood heater, fire place	Calor gas-stove	6 lights PV, (wind generator) Diesel gen set
H	Single storey house, timber	ca 1900	50	Wallas diesel 4kW	Wood stove, Calor gas-stove and -fridge	8 lights, Inverter for TV, computer, etc PV, wind generator. Gen set for heavier equip.
I	1½-storey house Separate one-room guest house	ca 1900	30 20	Firewood heater	Wood stove, Calor gas-stove	Paraffin oil lamps
J	1½-storey house, timber, with cellar	1980	80	Central heating w firewood boiler, solar collector, fire place	Wood stove, Calor gas-stove, electric fridge	10 lights, TV, fridge Inverter. 300W for computer and cell ph. PV
K	Timber house with work shop	1980	40	Paraffin oil heater	-	3 lights PV
L	Modern bungalow	1975	80	Firewood heater	Calor gas-stove	4 lights PV
M	Modern bungalow	1975	80	Firewood heater	Calor gas-stove	8 lights, computer. Inverter. 1000W

\*) Transistor radios in every household.

Appendix B. Inventory of equipment and appliances, expected changes and conditions for solar power at each house respectively.

House	Power supply	Battery bank	Year installed	Consumers	Desired/planned changes	Comments
A	PV-modules 2x100W DC/DC 24-12V Backup gen set 2,5kW	2x115Ah	2003	6x10W halogen lights Electric tools run by gen set Fridge w. frozen storage compartment run on bottled gas	El. fridge spring/summer/autumn Freezer summer/autumn TV, vacuum cleaner, pump Share in wind turbine	Shaded approx 11am-3pm summer *)
B	PV-modules 4x50W (vertical installation)	2x115Ah + 115Ah	2003	8x10W halogen lights	Omf: TV, vacuum cleaner Improved charger for electric boat engine	Shaded approx 11am-3pm summer *)
C	PV-module 80W 12V	110Ah	1990	No light Fridge, TV 12V	Fridge continuously spring/summer/autumn	Has sun only in summer, early morning and late afternoon Supply insufficient
D	PV-module 30W 12V Backup gen set 2,5kW	60Ah	ca1975	9x10W halogen lights	Fridge continuously sum./autumn TV	Shaded in summer (sun approx 9-14)
E	Transports charged battery from mainland	75Ah	-	2x10W halogen lights, TV	Share in PV and/or wind power (lacks suitable site on property)	Poor insolation conditions *)
F	PV-modules 30W 12V	115Ah	ca1975	4x10W halogen lights, TV 12V	Future residency demands are unclear	Perfect insolation conditions all year
G	PV-modules 3x60W 12V Wind 400W (out of order) Backup gen set 8kW 3- phase	120Ah?	1990	6 x 10W halogen lights (earlier more consumers were used)	Fridge, TV, radio etc. Inverter: vacuum cleaner	Between 1970-2000 residency times were April-August *)
H	PV-modules 2x60W 12V Wind ca 100W 24/12V Gen set 230V+battery charger	4x120Ah	1990	8x10W, Xenon o halogen lights Inverter: TV, computer, cell ph. Pump, coffee machine, vacuum cleaner run by gen set. (Fridge and hot water tank run on bottled gas)	Possibly an extra inverter for pump, coffee machine, vacuum cleaner	Between 1990-2000: permanent residency Shaded in the mornings *)
I	None (Paraffin lamps, bottled gas, fire wood)	None	-	-	Possible connection to house A	Excluded from the comparison
J	PV-modules 3x60W 12V (solar collector 0,6x2,5m)	2x200Ah gel	ca1975	10x10W halogen lights, TV 12V, fridge 12V Inverter300W: computer, cell ph.	Pump	Desires "simple look" Poor insolation conditions in summer
K	PV-module 30W	75Ah	ca1975	3x10W halogen lights		Guests and youth *)
L	PV-module 55W	115Ah	1998	4x10W halogen lights	Adds PV-modules, connection of two houses	Shaded early morning and evening *)
M	PV-module 83W	125Ah	1999	7x10W halogen, 2x8W lysr. Omf.1000W: dator, laddn.	Electric fridge summer/autumn, kitchen fan	*)

\*) Shaded all winter through (approximately November to February).

Appendix C. User patterns in the Vidinge case

The times of residency stated in the table are based on information from the owners. Stated times refer to the number of days per month that the house is being used. Example: 2 x 3 + 10 means that during this month the house is normally used on three separate occasions; twice for period of 3 days and once for 10 consecutive days. A full week is assumed to include 8 days, i.e. Saturday till Sunday the following week. D/A = total number of days in a year (Days per Annum).

House	No of inhabitants	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Sum D/A
A	2-4					2x3	10	3	3			2x2	4	30
B	2	7	2x3	2x3	2x3	3x3	3x3+10	3x3+8	2x3+8	2x3	2x2	2x2	10	108
C	2-4				2x2	3x2	2x3+10	2x8	3x3	2x2				55
D	2				3	3x2	2x2+10	2x3+8	2x8	2x2				57
E	1-2				2x1	2x2	2x2+5	2x2	2					21
F	2-3						8	2						10
G	2-6				3	3	2x2+5	3x2						21
H	2			2x2	2x2	2x8	30	31	31	2x3	2x2	2x2		130
I	2						8	2x8						24
J	4-6				3x3	4x3	2x3+10	31	3x3			3		80
K	2						8	sporadically						8
L	4-6				2x2	3x2	3x3+10	3x8	2x2					57
M	2-6				2	2x2	3x3+10	31	3x2	2x2	2			68
Sum Days per Month and 13 houses		7	6	10	37	72	193	187	94	24	10	15	14	669

## Appendix D: Power consumption of electric appliances

### Lighting

LED lights are an example of consumer products development. If the sizing of a PV-system earlier was made on the basis of 5-10 halogen lamps, totalling about 100 W, this can be reduced to 10 W using LED lights. However, the long life time of a LED light and the fact that its' energy consumption is so low, are two factors that combined actually present a risk for increased use of the lights (as people become less concerned about turning off the lights).

### Telephone

Vidinge has a landline connection. Popular are landline wireless phones, which permit use anywhere in the house and garden. Equally, answering machines are a priority for many people. Power consumption of this equipment is 5 W each.

A cell phone is also part of "standard" equipment. The charger for cell phone batteries (12V) requires up to 5 W.

### TV-set

When it comes to watching TV, many people express an interest in extended viewing times and in use of DVD/video equipment. As flat screen TV's become more common they are expected to become the preferred type of TV also in the holiday house.

An energy efficient TV-set typically requires 50 W. In addition, today a digital box is needed, requiring an extra 10 W.

Four hours of TV use per day is considered to be a suitable design basis for the vacation home, corresponding to 240 Wh/day.

### Radio

Radio listening is no longer restricted to news and weather reports, but instead the radio often stays on during the day. Power consumption of a common 12 V radio is estimated to 10 W. A design value for energy consumption should be set to 80 Wh/day.

### Refrigerator

In many of the Vidinge households, a 12 V compressor refrigerator is high on the list of desired appliances. Those who have a paraffin/gas driven fridge today would prefer to change it for an electric one, as its' ease of operation is valued as well as the avoided filling of fuel (and associated costs).

12 V compressor fridges come in several different models. The energy consumption is relatively independent of the size. It can be assigned a value of 300 Wh/day. Under the assumption that the fridge is placed in a cool environment, the consumption can be assigned a 50 - 70 % lower value during autumn and spring, which compensates the lower insolation on the solar modules during these periods.

### Freezer

Sometimes also a freezer is added to the list of desired electric appliances. For example, the opportunity to freeze food prior to transport or to store fish or meat would be appreciated.

12 V freezers are available in different sizes. A reasonable design value for the energy consumption of a large box is 300 Wh/day, i.e. the same as for a fridge. The freezer should be placed in a non-heated space, in the shade.

However, for reasons of operation reliability the energy supply to the freezer should be separated from other appliances. Preferably the freezer should have its' own PV-generation and battery. Therefore, a freezer is not included in the calculations.

#### Vacuum cleaner

This is a frequent request. Rechargeable handheld vacuum cleaners are available in 12 V designs, however of questionable quality and durability. The power need for a normal 230 V vacuum cleaner ranges between 1200 – 2000 W, that is 100- 160 A at 12 V. The electric engine also has a high start-up power and may require pure sinusoidal voltage. Operating times of about 0,5 hours per week corresponds to 150 Wh/day spread out over 7 days, but requires about 100 Ah extra battery capacity.

A vacuum cleaner is best operated by a gas- or diesel generator.

#### Microwave oven

A microwave oven is requested by some. The common 230 V design requires use of expensive sinusoidal inverters. It is required by the electronics of the oven and the high power, which corresponds to over 100 A.

There are 12 V micro wave ovens available with a power consumption of 750 W, equalling 65 A at 12 V. The microwave power for the 12 V oven is around 60 % or 450 W, which means that cooking time will be longer than in a 230 W oven that often has around double that power.

Occasional use around 10 Minutes per day gives an energy need of around 125 Wh/day.

#### Coffee machine

Some people also request a coffee / espresso machine. 230 V designs has a power consumption of around 700 W, i.e. the same order of magnitude as the microwave oven. But for the pure heating function of the coffee machine a cheaper inverter can be used.

12 V designs are available in different sizes. "1 cup"-size around 200 W (1 A, 6 minutes), can be connected to a normal 10-15 Amps cable. (In larger designs, i.e. 5 cups, the cooking time with 200 W will be up to ten times longer than boiling the water on a gas stove.)

12 V "5-6-cups" designs are available at 600 W (50 Amps, 10 minutes). This will require a separate connection to a battery (see microwave).

Using the coffee machine once a day or a full pot or for 3 times 2 cups will give an energy need of 300 Wh/day (the same as for a fridge or freezer!).

Instead of an electric coffee machine, coffee ought to be prepared on the gas stove.

#### Computer

Today, the computer is considered as important an appliance as the TV by many people, especially if an internet connection is available. Internet access

will become increasingly common with the development towards wireless connections.

On Vidinge, two phenomena can be noted, that mean increased energy need compared to only a decade ago.

Computers and the internet give better opportunities for many people to work from home. This means an increased energy need of the household due to the computer use in a day. But it also has an effect on the time spent in the holiday/weekend home, when this can be used as a work location too, at times.

For the younger generation the computer is an "indispensable tool" for many of their free time activities; notably music, computer games.

Laptop computers are often designed for 19 V. Direct current inverters DC12-DC19 Volts are available. The power need for such a lap top is typically 60 W.

Based on the above line of argument, a reasonable design value for the PV-plant is 4 hours/day (240 Wh/day), but supplemented by an extra battery capacity designed for 8 hours/day for 5 days (200 Ah).

#### Washing machine

Some people want a washing machine, especially for longer stays.

An ordinary 230 V washing machine typically demands 2500 W, e.g. 200 A/12 V. In addition, there is the need for running water. Those who wish to install a washing machine are recommended to operate it by means of a diesel gen set.

#### Water pump

Pumps to draw water from a well are available for 12 V, designed for about 7 bar and 3 litres per minute. Their power consumption is around 60 W. Assuming operation around 15 minutes per day (around 40 litres of water) gives an energy consumption of 15 Wh/day.

(If higher capacity is required for a washing machine, it is recommended to use a more powerful pump operated by the same generator as the washing machine.)

#### Hot water tank

To heat 3 litres of water per minute (see water pump) from 10 °C to 40 °C requires about 6000 W, or correspondingly 1050 Wh for a 10 minute shower. This is a task much better suited for a gas heater or solar collectors.

#### Electric chain saw and wood-chopper

These are two electric tools that some households consider very valuable.

The power required for both tools is around 1500 – 2000 W each. The high power level makes 230 V necessary, i.e. a powerful inverter would be needed. In the case of the wood-chopper, operating times can be lengthy; up to full days. 6 hours of operation equals 12000Wh!

A PV-plant obviously should not be designed for these requirements, but the tools should rather be operated by a diesel gen set.

## Appendix E: Choice of cable and other network components

**Feeder cable** for ground laying is available in standard design with PVC isolated PVC sheathed 4-conductor and earth of aluminium. The notation is AKKJ, or Cenelec SE-N1XV-AI.

The choice of 4-conductors permits coupling of the conductors in pairs and thereby achieves less voltage drop and power loss than would be the case with a 3-conductor.

Common sizes are:

- 4x95+29 mm<sup>2</sup>. (Fuse 160 A. Conductors connected in pairs thus will manage at least 320 A.)
- 4x150+41 mm<sup>2</sup>. (Fuse 250 A. Conductors connected in pairs thus will manage at least 500 A.)

**Service cable** for ground laying is available in standard design with PVC isolated PVC sheathed 4-conductor and earth of copper. The notation is EKKJ or Cenelec SE-N1xv-U.

The choice of 4-conductors permits coupling of the conductors in pairs and thereby achieves less voltage drop and power loss than would be the case with a 3-conductor. The earth wire is normally of the same size as the conductors but may be needed to balance the potential.

Common sizes are:

- 4x10+10 mm<sup>2</sup>. (Fuse 35 A. Conductors connected in pairs thus will manage at least 70 A.)
- 4x16+16 mm<sup>2</sup>. (Fuse 63 A. Conductors connected in pairs thus will manage at least 120 A.)

**Earth line and earth electrodes** are available in different designs. In ground a galvanised steel wire or copper conductor is often used. Because of the risk of corrosion in the sea environment and in passages between different soil types steel wire is unsuitable. (There are examples from Vidinge where steel wire has been cut off by corrosion in less than 10 years.) The choice is blank, i.e. non-isolated, copper wire or stainless steel wire.

Common sizes of copper wires are 25 mm<sup>2</sup>.

**Wiring cabinets.** There are cabinets in different standard sizes for connection of service cables to the feeder cable. A common size of such cabinets accommodates the wiring for up to three households.

**Connection and controlling equipment.** Suitable equipment for the connection of the single plant to the service cable is not available in the market.

This equipment should contain at least the following functions;

- a limitation of incoming feeder current, in order to protect the DC/DC regulator
- a function for the connection of outgoing power, that will know when the battery of the plant is full and the power production exceeds the own demand.

- Measurement of incoming and outgoing energy is preferred.

The principle for such equipment is described in chapter 3.

Preferably, a new standard regulator device should be developed which would include the above functions, rather than developing an extra device to use as a supplement to an old regulator. When connecting existing stand-alone PV-plants into a grid, it is likely that the majority of installations need to exchange their existing regulator regardless (e.g. from the frequently employed 12dc/12dc to the 24dc/12dc needed for the grid connection).

**Lightning protection** must be included.

## Appendix F: Calculations for cable sizing and network losses

### REQUIRED CABLE LENGTHS

A reasonably general estimate for cable lengths can be chosen by looking at average figures used by the surveyor offices. For example; in order for a household to independently manage water supply and sewage infiltration, the surveyor offices calculates with a minimum size for the block of land of 2500 m<sup>2</sup>, under good conditions. If the block of land includes rock and clay ground, these areas will be added. A detached property which is self-sufficient in water and sewage handling thus theoretically has an area of at least 2500 m<sup>2</sup>, and it normally ranges between 2500-5000 m<sup>2</sup>. This agrees with the conditions at Vidinge. Assuming a square block of land, the length of one side is between 50 and 70 metres.

#### **Feeder cable**

A reasonable estimate for required cable length is 25-35 metres per house, which would be the case if the feeder cable is laid out along the property border and the house is assumed to be placed in the middle of the property.

This agrees with the conditions at Vidinge. A survey at Vidinge shows that around 100 metres of feeding cable is are required for the case of 6 properties connected to one network. To this will come 30 m to reach suitable common PV-module placements and approximately another 5 m of spare and coupling waste per wiring cabinet. The latter must be considered in the cost estimation. In total; 150 m or around 25 metres per property. The remaining 6-7 properties can build a mini-grid with around 150+30+20 metres of feeder cable; again that is around 30 metres of cable per property. For the case of 12-13 properties connected to one mini-grid, a connecting feeder cable is required between the two mini-grid clusters, resulting in a total length of 390 + 40 metres or around 35 metres per property.

The feeder cable sizing lengths are taken from the network layout in figure Figure 4.2 in chapter 4. In a general cost analysis a feeder cable length of 35 metres per property can be assumed. In the Vidinge case actual lengths from the network lay-out is used with an added 30 metres to reach a common PV-module placement, and an extra 5 m per wiring cabinet.

#### **Service cable**

If the house is placed in the middle of the property, assuming property size as above, the distance from property border to house will be between 20 and 35 metres.

This is also the case at Vidinge. A survey of the distance between house and a planned connection to feeder cable for the mini-grid including 6 households, shows that the distance is around 20 metres for 5 of the households and around 35 metres for one. In the case of 12-13 properties in the mini-grid, the distance in four of the additional cases is 20 metres and for the remaining 3 around 35 metres.

Including an extra 5 metres per house for reaching the right connection spot in the house and for the wiring cabinet being placed at some height above ground, the total cable length required will be 25 – 40 metres per property.

For the sizing of the service cable the distances 25 (20+5) metres and 40 (35+5) metres were used. The longer length of cable is compensated by choosing a larger cable area.

#### CALCULATION OF VOLTAGE DROP

##### **Feeder cable voltage drop**

The feeder cable is of aluminium, normally of the size 4x95 mm<sup>2</sup> or 4x150 mm<sup>2</sup> conductors supplemented by a thinner earth conductor.

95 mm<sup>2</sup> can handle up to 160 A. Conductors connected in pairs can handle up to 320 A. Thus, this is not a value that limits any of the alternatives.

The resistivity for aluminium is 0,027 Ωmm<sup>2</sup>/meter.

The resistance for 4x95 mm<sup>2</sup> cable (incoming and outgoing) with conductors coupled in pairs is  $0,027/95 = 0,29 \times 10^{-3}$  Ω/m.

The resistance for 4x150 mm<sup>2</sup> cable with conductors coupled in pairs is  $0,027/150 = 0,18 \times 10^{-3}$  Ω/m.

Voltage drop in feeder cable is calculated from actual length and currents below

##### **Service cable voltage drop**

The service cable is of copper, normally of the size 4x10 mm<sup>2</sup> conductors + earth. For long distances 4x16 mm<sup>2</sup> may be used or even 4x25 mm<sup>2</sup>. For longer distances a feeder cable should be considered instead.

10 mm<sup>2</sup> can handle up to 35 A. Conductors connected in pairs can handle up to 70 A. Thus, this is not a value that limits any of the alternatives.

The resistivity for copper is 0,0172 Ωmm<sup>2</sup>/meter.

The resistance for 25 metres 4x95 mm<sup>2</sup> cable (incoming and outgoing) with conductors coupled in pairs is  $0,0172 * 25 / 95 = 0,043$  Ω.

The alternative "Standard 1" thus involves a voltage drop of (RxI)  $0,043 \times 7 = 0,3$  V. For a 40 meter long cable it translates to around 0,5 volt. If 4x16 mm<sup>2</sup> were used instead for 40 metres, the voltage drop would be 0,3 volt.

The alternative "Standard 2" has a voltage drop of (RxI)  $0,043 \times 20 = 0,86$  V. For a 40 meter long cable it translates to around 1,37 volt. If 4x16 mm<sup>2</sup> were used instead for 40 metres, the voltage drop would be 0,86 volt.

The alternative "Standard 3" has a voltage drop of (RxI)  $0,043 \times 13 = 0,56$  V.

#### CALCULATION OF ENERGY LOSS

The choice of feeder cable size is made on basis of calculated and acceptable voltage and energy losses for the distances on Vidinge. The network losses are calculated from total losses from the separate parts (resistance x current) divided by the total supply (voltage x current).

A "worst case scenario" is used in the calculations by assuming that the total power demand is met by a common PV plant (and perhaps added gen set). This may be an option in the real Vidinge case, due to the problems of shading for many of the properties. A PV-plant located at one of the proposed sites in the layout (Figure 4.2) would in principle double the panel efficiency compared to current real conditions. The common PV-plant(s) are assumed to be connected to the network by a feeder cable of 30 metres.

Below, the calculation of voltage and energy losses is presented for the case "Standard 2" which has the highest amperage. The calculation is made for the cable from the common feeding point G2 to house A, farthest away from G2. Since this network happens to be symmetrical with reference to distances, the same result will be valid for feeding from G1 to property F.

Voltage drop, 6 households (A – F), "Standard 2" (20A/household)

With 4x95 mm<sup>2</sup> cable:  $\Delta V = \sum R_x I + \Delta V_{\text{service cable}} = 30 \times 0,29 \times 10^{-3} \times 6 \times 20 + 40 \times 0,29 \times 10^{-3} \times 5 \times 20 + 20 \times 0,29 \times 10^{-3} \times 3 \times 20 + 40 \times 0,29 \times 10^{-3} \times 20 + 0,86 = 2,784 + 0,86 = 3,64 \text{ V}$

With 4x150 mm<sup>2</sup> cable:  $\Delta V_{G2-A,150} = 1,76 + 0,86 = 2,62 \text{ V}$

**Network losses, 6 households (A – F), "Standard 2" (20A/household)**

With 4x95 mm<sup>2</sup> cable:

Losses  $G2-A,95 = [\sum R_x + \sum R_x I^2 \text{service cables}] / [U \times I] = [30 \times 0,29 \times 10^{-3} \times (6 \times 20)^2 + 40 \times 0,29 \times 10^{-3} \times (5 \times 20)^2 + 20 \times 0,29 \times 10^{-3} \times (3 \times 20)^2 + 40 \times 0,29 \times 10^{-3} \times 20^2 + 6 \times 0,043 \times 20^2] / [24 \times 6 \times 20]$

With 4x150 mm<sup>2</sup> cable:

Losses  $G2-A,150 = [169 + 103] / 2880 = \mathbf{9,5 \%}$

The calculations show that the network losses are acceptable even with the highest amperage of 20 A. The choice of cable size is made on basis of the voltage drop. In a "worst case" the calculations show that the voltage drop with a 4x95 mm<sup>2</sup> cable borders to unacceptable, and 4x150 mm<sup>2</sup> should be chosen.

Analogous calculations are made for the second cluster; households G – M with power supply from a common plant G2 or G3. The voltage drop in this case is 7,0 V and 4,8 V respectively with 4x95 mm<sup>2</sup> cable and 4,8 V and 3,4 V respectively with 4x150 mm<sup>2</sup> cable.

The 4x150 mm<sup>2</sup> cable should be chosen. This also corresponds with the larger power distributing companies' rules of thumb for 230 V, which says to choose the next size up from 4x95 mm<sup>2</sup> for distances exceeding 100 metres.