Presented at the 2nd Workshop on the Future Direction of Photovoltaics
Tokyo, Japan
2-3 March 2006

THE CRYSTALCLEAR INTEGRATED PROJECT
Next generation crystalline silicon PV technology from lab to production

CRYSTALCLEAR

Wim C. Sinke
Project Manager CrystalClear
Energy research Centre of the Netherlands, POB 1, NL-1755 ZG Petten, The Netherlands
E-mail: pmo@ipcrystalclear.info
Public website: www.ipcrystalclear.info

ABSTRACT: CrystalClear is one of the first Integrated Projects to be carried out in the 6th Framework Program of the European Union. It runs from 1 January 2004 to 31 December 2008. CrystalClear is intended to be the main vehicle for EU-supported research and development on advanced industrial crystalline silicon PV technology. This paper provides comprehensive information on the project background and aims, the management structure, and the research program. Some best practices are described for use in ongoing and future EU projects. In addition, the paper gives selected results obtained in the first stage of the project. For a detailed description of publishable research results the reader is referred to the list of publications that can be accessed through the CrystalClear public website.

Keywords: Cost reduction, PV Module, Silicon, EU Project.

1 GENERAL PROJECT INFORMATION

CrystalClear (CC) is one of the first Integrated Projects (IP's) to be carried out in the 6th Framework Program of the European Union. CC is intended to be the main vehicle for EU-supported research and development on advanced industrial crystalline silicon PV technology. The project runs from January 2004 to December 2008 and has a total budget of 28 M€. Of this amount 16 M€ will be contributed by the EU and 12 M€ by the 16 partners:

Industry partners:
- BP Solar (ES);
- Deutsche Cell (DE);
- Deutsche Solar (DE);
- Isofoton (ES);
- Photowatt (FR);
- REC (NO);
- Scanwafer (NO);
- Shell Solar (DE);
- RWE Schott Solar (DE).

Universities:
- Konstanz (DE);
- UPM-IES (ES);
- Utrecht (NL).

Research institutes:
- CNRS PHASE (FR)
- ECN (*coordinator*, NL);
- Fraunhofer-ISE (DE);
- IMEC (BE).

2 EXPECTED IMPACT

CrystalClear concerns, as one of the main topics, the *direct manufacturing costs* of PV modules. In order to appreciate the expected impact of the project it is necessary to place the project aims in a broader context. Direct manufacturing costs are the main contributor to full costs, which in turn are the basis for selling prices. PV modules form the heart of any solar energy system and usually account for some 60% of the turn-key price of roof-top installations. Current turn-key system prices are typically around 5 €/Wp excluding VAT [1]. Obviously one may find lower as well as higher prices depending on a variety of parameters.

Figure 1 shows the possible reduction of the turn-key prices of such installations over time, as reported by the Photovoltaic Technology Research Advisory Council in [1]. The objective of the CrystalClear project is to enable a price reduction from current levels to roughly 3 €/Wp, which typically corresponds to electricity generation costs of 15 to 40 eurocents per kWh, depending on location in the EU [2]. This is an improvement of 40% over the present situation and brings the costs into the range of consumer electricity prices, which is often considered to be the first major hurdle to overcome on the way towards large-scale application of photovoltaics.

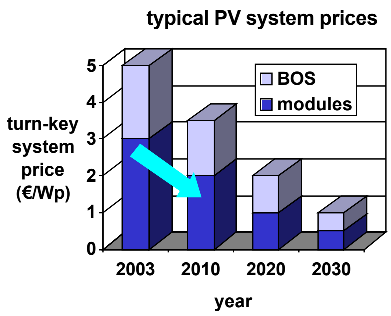

Figure 1: Possible development of turn-key system prices according to [1], divided into modules and BOS-components. The arrow indicates the portion CC aims at.

Since the CrystalClear project does not address the Balance-Of-System (BOS), success of CrystalClear will not be sufficient to obtain the price reductions shown in Figure 1. It is expected, however, that there will be considerable efforts in the BOS-area as well so that the combined results will be sufficient.

CrystalClear also aims to improve the environmental quality of the modules and the corresponding systems. An important parameter in this respect is the so-called energy pay-back time (EPBT), that is the time a module has to operate to generate the same amount of energy (in equivalent terms) as was needed to manufacture it. The EPBT is linked to the effectiveness of the use of PV to reduce greenhouse gas emissions.

The aim of CrystalClear is to enable a decrease of the energy pay-back time of photovoltaic systems from 1.5-4 years [3] to roughly 1-2 years. Note that the range refers to different locations and the corresponding insolation (North-West and Central Europe versus Southern Europe) as well as to different wafer technologies. This will be achieved primarily as a spin-off of reductions in silicon consumption per watt-peak of module power, further increasing the already huge long term potential of PV to reduce CO_2-emissions.

In addition CrystalClear aims to reduce the environmental impacts of PV modules by 20% per unit area. This strengthens the position of PV as a clean generator of electricity.

3 BACKGROUND AND AIMS OF THE PROJECT

Over the past three decades industrial crystalline silicon PV technology has shown impressive growth towards technological and economic maturity. This is evidenced by the fact that the experience curve for PV modules, which is almost exclusively determined by crystalline silicon, is characterized by a progress ratio of approximately 80% over the same period [4]. In other words, typical selling prices have decreased by 20% for every doubling of the cumulative global sales. The growth towards maturity can also be seen from the increase of module efficiencies and from the narrowing of the gap between laboratory results and manufacturing practice. Most commercial modules now have active area efficiencies in the range of 13 to 16% (total area efficiencies between 11 and 14%) [5], while laboratory record cell efficiencies are typically between 20 and 25% for the different types of crystalline silicon materials [6]. The latter range shifts upwards only very slowly because processes and materials used in leading laboratories are close to perfect. In contrast, processes and materials used in production still have significant room for improvement, and thus allow for a further increase in commercial module efficiencies. The main challenge is to combine such an efficiency increase with the necessary drastic reduction in cell and module manufacturing costs, and with enhanced environmental characteristics, while maintaining or even improving product quality and applicability. These, in a nutshell, are the main objectives of CrystalClear, which have been summarized as follows:

- research, development, and integration of innovative manufacturing technologies which allow solar modules to be produced at a direct manufacturing cost of 1 €/Wp in next generation plants;
- improvement of the environmental profile of solar modules by the reduction of materials consumption, replacement of materials and designing for recycling;
- enhancement of the applicability of modules and strengthening of the competitive position of photovoltaics by tailoring to customer needs and improving product lifetime and reliability.

To reach these goals, CrystalClear is organized in 8 Subprojects (see Figure 2), 5 of which deal with a specific part of the production chain. In addition, one Subproject covers all sustainability aspects, while another is dedicated to cost calculations, internal technology roadmapping, communication, and integration of results from Subprojects into an overall approach towards module manufacturing. Finally, one Subproject is devoted to management of this large project consortium and to communication with the EC project officers and contracting departments as well as with the public and the PV community.

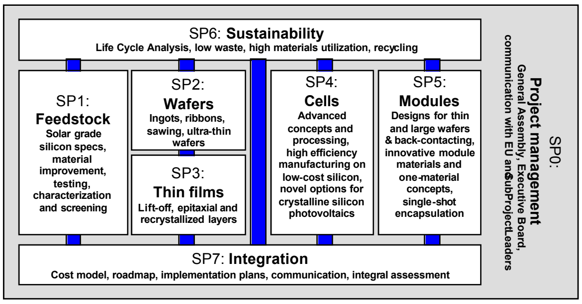

Figure 2: CrystalClear project structure with main research topics. SP = Subproject.

The knowledge base of crystalline silicon photovoltaics is very broad and solid compared to other PV technologies. This is a result of intensive research in the PV sector itself, but certainly also of achievements in the semiconductor electronics sector during half a century of rapid growth. It is now time to harvest from this knowledge by bringing together a group of key players and making the crucial next step: developing a dedicated and advanced manufacturing process for cells and modules. The structure of an Integrated Project is ideally suited for this, since it is literally integration of knowledge in the entire consortium and integration of process steps that have to make the difference.

4 SUBPROJECTS

In the following paragraphs a brief introduction to the subprojects is given, along with examples of research issues addressed in the first stage of the project.

4.1 SP0 Project management

The CrystalClear consortium has set ambitious goals. The cooperation of many and competing parties is a new and complex phenomenon. A solid structure is required to cover the decision-making procedures, the responsibility structure and the financial procedures. A project management structure has been set-up suited to the actual research being done at the work package level.

The following levels of management have been created:

- *General Assembly (GA),* with all partners represented, can be seen as the 'shareholders' meeting.

- *Team Leaders (TL),* for each partner there is one central contact and primary responsible person.
- *Coordinator,* who provides the chairman of the Executive Board and the General Assembly and is the liaison to the European Commission.
- *Executive Board (EB),* which carries overall responsibility for the day-to-day management and is supported by the Project Management Office (PMO) on all management activities.
- *Research Board & Industry Board* which both advise the Executive Board on content-related issues during the running of the project. The Industry Board is responsible for the "quality of the work regarding implementation and application" and the Research Board is responsible for the "scientific and technological quality of the work".
- *SubProject Leaders (SPL),* who are each responsible for one of the 8 subprojects, which are in turn divided into subjects and work packages. The SPL is in most cases a representative of one of the participating institutes because of the emphasis on research in these Subprojects. One subproject, SP7 on project integration and implementation, is led by an industry partner.
- *Work Package leaders (WPL),* who are responsible for work packages, the level at which the actual research is being carried out in cooperation between the work package coworkers. The WPL is also responsible for the deliverables within his or her work package.

4.2 SP1 Feedstock

CrystalClear is dedicated to crystalline silicon modules. The solar cells in such modules are made of very high purity silicon, the so-called feedstock. Silicon is, after oxygen, the most abundant element in the crust of the earth. It is produced in large quantities by reaction of quartz (silicon oxide) and cokes (basically carbon) at high temperature in electric arc furnaces. For solar cells (as well as for microelectronic chips) a high grade of silicon is required. Only then can the electrical properties be controlled sufficiently to allow use in devices. It is custom to speak about "solar grade" and "electronic grade" material. The production of this high-purity silicon requires advanced equipment, is expensive and energy-intensive. Until now, the PV industry has used surplus and "off-spec" electronic grade silicon from the microelectronics industry. This is however a limited source, which can no longer fulfill the needs of the rapidly growing (recently by 30 to over 50% per year) PV industry. Assuring security of silicon supply has therefore become one of this industry's main challenges [7].

Worldwide, several alternative manufacturing methods for high-purity silicon are under development. These methods aim at combining sufficient quality for use in high-efficiency solar cells with reduced cost compared to today's mainstream electronic grade silicon production. One of the main aims of Subproject 1 in CrystalClear is to test silicon from pilot production of these alternative methods on its suitability for use in advanced solar cell production, see Figure 3. After initial screening on some basic properties the material is tested "in real life" by several industrial and institute partners, and feedback is provided to the manufacturer.

Figure 3: Granular solar grade silicon feedstock before melting and subsequent directional solidification to form a multicrystalline silicon ingot (photo Deutsche Solar).

The other major aim of SP1 is to gain better scientific understanding and practical know-how on solar grade silicon. In SP1 available materials are studied in detail, but also model materials are produced and investigated, with emphasis on the impact of chemical impurities in the silicon on solar cell performance. This will result in well-founded specifications for major impurities in solar grade silicon and will allow design of optimum processes for silicon production as well as dedicated cell manufacturing processes.

4.3 SP2 Wafers

Once high-purity (solar grade) silicon has been obtained (see SP1, Feedstock) it has to be brought into a form suitable for solar cells. CrystalClear is about crystalline silicon in the form of wafers. In addition to the purity of the silicon used, the crystal quality determines to a large extent the solar cell efficiency that can be obtained. This crystal quality, in turn, is determined by the crystallization method and process control. In most cases silicon wafers are obtained by ingot crystallization, yielding large blocks of crystalline silicon, followed by sawing. Subproject 2 focuses on the two crucial steps required to turn feedstock into wafers: ingot crystallization and wafer sawing. First emphasis will be on achieving a higher productivity of the crystallization equipment (the furnaces), by applying larger crucibles (see Figure 4) and by better usage of the capacity. This will lead to an increase of the ingot weight by about 80%. Second, the utilization of ingot material will be increased dramatically by several improvements of the sawing process. With standard wire-sawing the wafer size will be increased from typically 125 x 125 mm^2 today to possibly 210 x 210 mm2. In a parallel development the wafer thickness will be decreased from about 200-300 µm today to 100-150 µm, while the kerf width will be reduced to less than 200 µm. Thus the consumption of silicon per Wp is expected to fall by about 40%.

Figure 4: Newly made 400 kg multicrystalline silicon ingot (photo Deutsche Solar).

Using novel cutting processes based on the use of lasers instead of saws, in the longer term the wafer thickness may even be decreased to 100 µm or less, at a kerf width as small as 100 µm. As the cutting-induced surface damage is expected to be much lower with this technique, damage etching (usually removing several tens of microns of material) can probably be avoided and more silicon can be utilized.

In addition to the work on ingots and sawing or cutting, research will be done on an alternative method for wafer formation, namely ribbon growth (EFG, Edge-defined Film-fed Growth). More specifically, the compatibility of new feedstock materials (see SP1) with this ribbon technology will be investigated. Further, ribbon material made in other projects by the Ribbon-Growth-on-Substrate (RGS) method will be tested using process techniques developed in CrystalClear (see also SP4).

4.4 SP 3 Thin film

An important approach in CrystalClear towards cost reduction (as well as efficiency improvement) is the use of thin silicon wafers made by sawing or ribbon growth, see SP2. The basis for cost reduction here is the smaller consumption of silicon per unit of module power. Another research line pursued in the project is that of the use of so-called thin-film “wafer equivalents”. In this case a thin (typically 10-20 µm), high-quality silicon layer is deposited onto a cheap substrate such as low grade silicon or ceramic material. Depending on the method used, the silicon layer needs to be recrystallized after deposition to obtain a sufficiently high crystal quality. An alternative route is the preparation of thin free-standing films by a “lift-off” method, see Figure 5. Here the silicon films are formed on a high-quality silicon substrate, but they are subsequently removed and the substrate may be reused. The lift-off films may be processed and used as such for special applications, but for power modules they are most likely attached to a cheap substrate.

If well designed, the cell properties determined by the thin active layer can be very good, while the costs may be reduced both because of the small amount of high-grade silicon used and because no wire sawing is needed. Obviously, the costs of film deposition or formation should also be low to obtain the desired result.

There are many different concepts for thin-film silicon-based solar cells. The wafer alternatives investigated in CrystalClear have an important short and medium term potential since they can be processed in standard crystalline silicon cell fabrication lines, employing basically the same processes as used today. The work in this subproject is aimed at achieving efficiencies comparable to those of solar cells based on cut wafers or ribbons, but at lower manufacturing cost.

Figure 5: Lift-off silicon film (photo IMEC).

4.5 SP4 Cells

Solar cell manufacturing is a key issue in cost reduction strategies for photovoltaics. There are many different ways to tackle production costs per watt-peak of module power, and most of those relate in some way to cell manufacturing: enhancing cell efficiency, using thin and large silicon wafers, processing low-cost material, increasing process quality, yield and throughput, and implementing cell designs to allow for low-cost module assembly (such as back-contact schemes, see Figure 6). CrystalClear deals with each of these topics in SP4.

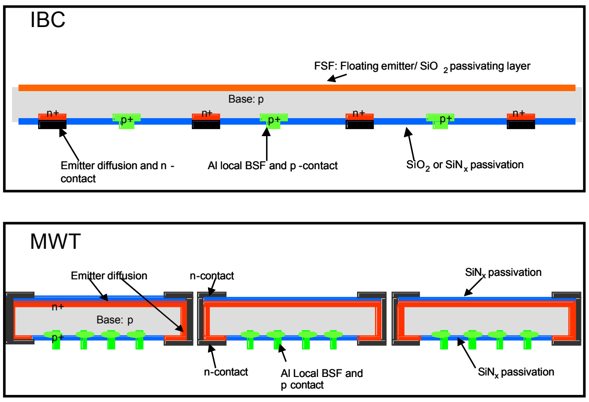

Figure 6: Two back-contacted cell & corresponding module concepts CrystalClear focuses on: the Interdigitated Back Contact (IBC) cell and Metallization Wrap Through (MWT) cell.

In addition to advanced cell concepts, the high-efficiency potential of novel low-cost silicon materials and the possibilities of “photon management” are investigated, the latter in close collaboration with the Full Spectrum Integrated Project. The term "photon management" refers to the shaping of the solar spectrum (by conversion of light) such that a better match with the sensitivity of crystalline silicon is obtained and higher efficiencies come within reach.

Advanced manufacturing technologies such as plasma processes and new in-line texturization will be further developed and evaluated. Industry will carefully accompany the work of involved institutes and universities to guarantee a fast technology transfer. An evaluation matrix for all concepts and processes including cost reduction calculations aids in effective focusing on the most promising technologies.

Dedicated production techniques, concepts and processes for very thin (<200 μm) and large (up to 210 x 210 mm^2) wafers will also be developed.

The combined activities of SP4 and related SP's can lead to a decrease of production costs per watt peak of typically 50%.

4.6 SP5 Modules

The research and development efforts of the Subprojects 1 to 4, ranging from silicon feedstock to finished cells, come together in SP5, which deals with the final "product" of CrystalClear: the solar module. The key overall goals of the project are expressed in module terms because these are directly relevant for cost reduction of photovoltaic systems and thereby for the generation cost of solar electricity.

SP5 aims at developing advanced module concepts and corresponding highly automated and fast module assembly technologies. These should of course be fully matched with the cells developed in SP4.

Important boundary conditions are excellent reliability and lifetime and an enhanced environmental quality. For instance, the materials used in module assembly and the module design have a major influence on the possibilities for reclaim and reuse of materials. A further aim is to obtain flexibility in design to allow tailoring modules to customers' needs.

Research in SP5 is specifically targeted at advanced cell interconnection schemes for large and thin wafers and for back-contact cells (see Figure 7), at new module materials, and at "single shot" encapsulation as well as one-material concepts.

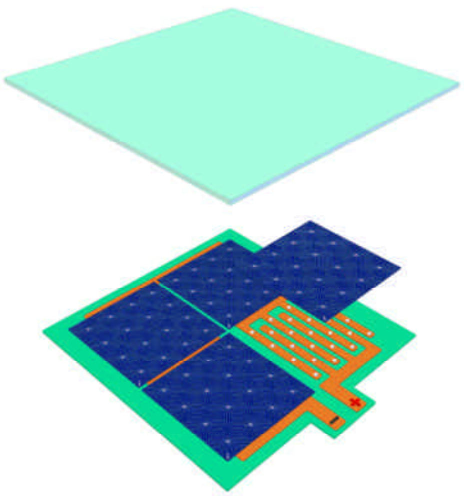

Figure 7: Schematic exploded view of a module based on back-contacted solar cells (drawing A.C. Tip, ECN).

Results from SP5 should enable a reduction of the add-on costs for module manufacturing by more than 50%.

4.7 SP6 Sustainability

SP6 is dedicated to the optimization of crystalline silicon photovoltaics as a sustainable energy technology. Although photovoltaics is based on the use of sunlight and therefore a fully renewable energy technology, its environmental quality (sustainability) is dependent on the energy consumption during manufacturing and on the materials used. These issues are closely related to the topics covered in SP1 to SP5, which emphasizes the importance of SP6 in the whole of CrystalClear. The activities cover two main aspects:

- further development of module recycling technology, which also allows for recovery and reuse of silicon wafers;
- analysis of the environmental impacts of module manufacturing by means of the Life Cycle Assessment (LCA) method.

The objectives are to achieve a 20% reduction per unit area of the environmental impacts of PV modules, and to decrease the energy pay-back time of photovoltaic systems from the current values of 1.5-2.5 years (Southern Europe) and 2.5-4 years (North-West and Central Europe), respectively, to roughly 1-2 years, see also [3] and Figure 8.

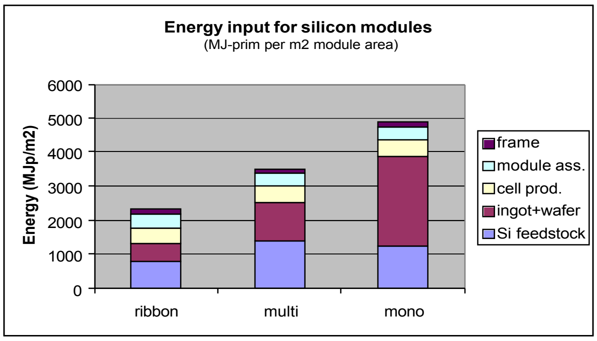

Figure 8: Comparison of typical energy input for manufacturing of various types of crystalline-silicon modules, situation 2005 [3].

The research and development on recycling technology will mainly be done in a pilot recycling facility at one of the industry partners, which is already in operation. Other partners will offer new and existing module types for testing in the recycling process. The LCA parameters obtained will be used as one of the drivers in the selection of optimal CrystalClear technology options (from feedstock to completed module).

4.8 SP7 Integration

Through innovation and detailed evaluation the CrystalClear project aims to demonstrate substantial reductions in the cost of solar module manufacture. All parts of the module value chain are being evaluated from feedstock production, through wafer fabrication and cell processing to module assembly. However, it is important that not one aspect of this chain is optimized without due regard to the others or to the sustainability of the overall technology. SP7 will be the focus for this integration. Two key tasks within SP7 are central to this activity:

- the development of a cost model to provide a basis against which the benefits of new processes can be evaluated and the overall project objective demonstrated, see Figure 9;
- critical and continuous assessment of the emerging technologies from within the project to ensure

compatibility and convergence with the final project goals.

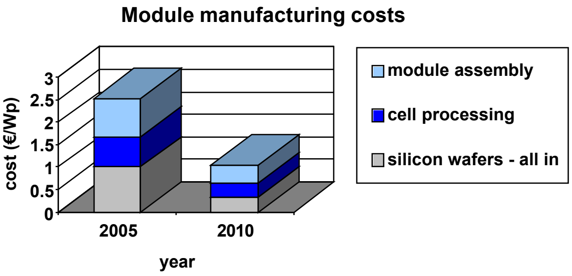

Figure 9: Typical cost build-up of crystalline silicon modules: situation 2005 compared with projects aims.

Other associated tasks within SP7 include:

- establishing a technology roadmap for crystalline silicon photovoltaics with which the project can be steered and benchmarked against international activities;
- organization of workshops and conferences to disseminate results and ensure coordination between all project activities;
- promote and foster student exchanges between participating organizations;
- a socio-economic impact study of the factors that will influence the exploitation of the technology.

5 MANAGEMENT LESSONS LEARNT

In the first year of operation CrystalClear partners and consortium management have gained experience with the new and complex EU-instrument of Integrated Projects. Some of the conditions for success are found to be:

- the introduction of regular face-to-face and telephone meetings on a subproject or work package level;
- introduction ánd use of a versatile web-based project management tool [8], which serves as common archive, work space, source for contact details, etc.;
- the development of standardized and ready(easy)-to-use templates for reporting and planning purposes.

6 CONCLUSIONS

CrystalClear is up and running since the end of the "ramp-up" period, that was mid 2004. The cooperation of 16 expert partners (with an estimated total number of 80 to 100 researchers involved) in the field of crystalline silicon photovoltaics can bring this technology to further maturity in terms of performance, design, and economics. Achieving the goals of CrystalClear will be an important contribution to fulfilling the overall targets for Europe as formulated by PV TRAC [1].

7 ACKNOWLEDGEMENTS

The author wants to thank the CrystalClear partners for providing valuable input for this paper.

The EC is gratefully acknowledged for financial support to CrystalClear under Contract number SES6-CT_2003-502583.

8 REFERENCES

[1] E. Perezagua et al., "A Vision for Photovoltaic Technology", Report by the Photovoltaic Technology Research Advisory Council (PV TRAC), European Communities (2005), publication nr. EUR 21242.
[2] Roughly assuming a performance ratio of 85%, 3% real interest rate, 20 years economic lifetime, and 1% operation and maintenance costs per year. Note that the choice of these parameters determines the conversion rate from €/Wp to €/kWh. As yet there is no internationally accepted standard set of parameters.
[3] E.A. Alsema and M.J. de Wild-Scholten, Proceedings EUPVSEC20 (Barcelona, Spain), p.3173 (2005).
[4] Results from the EU FP6 "Photex" project; G.J. Schaeffer and H.H.C. de Moor, Proc. 19th EUPVSEC (2004) 3415.
[5] See, for instance, K.H. Diefenbach, Photon International, February 2005, p.49.
[6] M.A. Green, K. Emery, D.L. King, S. Igari and W. Warta, Solar Cell Efficiency Tables (Version 25), Progress in Photovoltaics 13 (1) (2005) 49.
[7] J. Bernreuter, Sun & Wind Energy 1 (2005) 76.
[8] CrystalClear has selected a tool developed for FP6-projects by DiVa, which is based on Microsoft software (SharePoint), see www.diva.nl.