Ann. Telecommun. (2010) 65:739–756
DOI 10.1007/s12243-010-0188-9

A funding and governing model for achieving sustainable growth of computing e-infrastructures

Ashraf A. Bany Mohammed · Jörn Altmann

Received: 31 May 2009 / Accepted: 17 June 2010

Abstract The current access policies and funding schemes of computing e-infrastructures represent a huge challenge for the sustainable growth of computing e-infrastructures and a serious jeopardy for investments made into these e-infrastructures. In order to be able to address these issues, the economics of computing e-infrastructures has to be understood thoroughly. As a first step in this direction, this paper conducts a set of computing e-infrastructure case studies and discusses the economic issues of different global computing e-infrastructure efforts. The analyses results show that the major shortcomings that need to be resolved are the insufficient involvement of the private sector in the development of computing e-infrastructures, the restricted user access to e-infrastructure resources, and the lack of sustainable funding. As a solution to these shortcomings, we propose a new funding and governing model for computing e-infrastructures. It follows a token-based market mechanism that allows a business-oriented operation of the computing e-infrastructure. We argue that this new model fosters the transition towards a sustainable computing e-infrastructure, being another requirement for successfully implementing the cloud computing vision. Our arguments are supported by an analytical analysis.

J. Altmann (✉)
Technology Management, Economics, and Policy Program,
Department of Industrial Engineering, College of Engineering,
Seoul National University,
599 Gwanak-Ro, Gwanak-Gu,
Seoul 151-744, South-Korea
e-mail: jorn.altmann@acm.org

A. A. Bany Mohammed
Management Information System Department,
Faculty of Administrative and Financial Sciences, Petra University,
P.O. Box 961343, 11196, Queen Alia Intl. St.,
Amman, Jordan
e-mail: abany@uop.edu.jo

Keywords Grid and cloud economics · Business models · Funding · Governance · Case study analysis · Sustainability · Grid computing · High-performance computing · Token-based market mechanism · Computing services · Analytical modeling

1 Introduction

The cloud computing vision promises to offer ubiquitous computing and knowledge services to academia and industry in the future. The foundation for this has been set in the past few years. During that time, computing e-infrastructures endured core advancements (e.g., grid computing technology, service-oriented computing [1–4]) and achieved a wide acceptance in an effort to build the global computing e-infrastructure. Many computing e-infrastructures were initiated, and countless innovative hardware, concepts, middleware, and applications were introduced. Yet, beside a few works on analyzing participation [5], the generation of sustainable business models around these computing e-infrastructures is still challenging and is missing solutions.

In fact, the development of a global cloud computing e-infrastructure is a complex task, where a working infrastructure is more than just the technical elements (i.e., hardware and software) involved. It is a socio-technical arrangement, involving complex relationships between stakeholders of various problem domains. Therefore, funding, management, governance, synchronization, and harmonization of e-infrastructures, which work across domains (i.e., firms, organizations, and nations), across nations, across disciplines (e.g., biotechnology, astronomy, communication, agriculture), and across technologies (e.g., PC, PDAs, mobile phones), are difficult tasks.

In tackling these tasks, this study seeks to understand the following main research questions: (a) What models of funding and governance are currently applied for computing e-infrastructures? (b) How do these models influence the development and utilization of computing e-infrastructures? (c) How can the transition towards a sustainable e-infrastructure, which is another requirement for successfully implementing the cloud computing vision, be supported? (Note: Within this paper, we use the term sustainability according to the definition that, over the course of time, external funding (e.g., funding from public bodies) of a project is replaced by revenue from users using the outcome of the project. A wider definition can be found in [6].)

Due to the lack of statistical data on computing e-infrastructures, this study uses a comparative, qualitative analysis of 12 major computing e-infrastructure projects from three different continents to answer the three research questions. Projects were selected to capture the state-of-the-art in computing e-infrastructure (i.e., grid computing infrastructures, computer network infrastructures, and computing service infrastructures). Although we bound our work to aspects of funding and governance, we also tackle network composition, interconnection, security, and access provisioning of those e-infrastructures. The data for this study were collected from project Web sites, presentations, deliverables, and research papers.

The remainder of this paper is organized as follows: The next section presents background on concepts of e-infrastructures, classical infrastructures, and interconnection technology. Section 3 provides the case study analyses of computing e-infrastructures, with focus on funding and governance. Based on these results, section 4 provides a comparison between computing e-infrastructures and classical infrastructures. Section 5 presents the new model for funding and governance of computing e-infrastructures and analytical models showing the advantages of the proposed funding and governance model. Finally, section 6 provides market and policy recommendations, and section 7 concludes this paper.

2 Background and concepts of infrastructures

2.1 The concept of e-infrastructures

Throughout the literature, e-infrastructures have been coined by different terms and definitions. For example, the European Commission considers an e-infrastructure "a set of persistent services and processes bringing the power of distributed ICT-based resources to a virtual community as a complete collection of tools, facilities and digital resources that are needed nowadays for advanced scientific collaboration" [7]. In the UK, the e-Science program describes e-infrastructures as "the next generation infrastructure that supports the global collaboration in key areas of science" [8]. Whereas in the USA, the Office of Cyberinfrastructure of the National Science Foundation defines e-infrastructure as the "collective services and resources that are characterized by high computational power and other computing and information processing services available to advance the research communities" [9]. Despite the differences in the naming of e-infrastructure components, the core concepts are identical [10]. All definitions stress the availability of information and communication technology as a basic infrastructure.

In all definitions, the structure of the computing e-infrastructure is commonly composed of three layers: (a) physical layer, (b) middle layer, and (c) logical service layer.

The physical layer consists of hardware resources (e.g., servers, high-performance computers, and sensors), software resources (e.g., operating systems and statistical analysis software), data resources (e.g., coordinates of maps), and a high-speed broadband network. The middle layer uses grid middleware and complementary applications for offering a set of services that enable the interconnection of the different physical services. The logical service layer is shaped by coupling these services with knowledge and human expertise (Fig. 1). Variations of this model can be found in [11, 12].

On top of the three e-infrastructure layers, the cloud vision can be implemented. The cloud will support governments, businesses, and research based on a set of common interfaces. It makes information and communication resources (e.g., utility computing, customer relationship management) available through a service model.

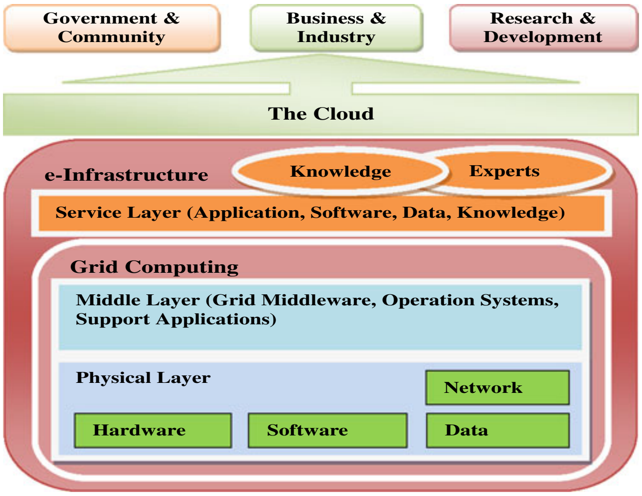

Fig. 1 A high-level conceptualization of e-infrastructures and its relation to the cloud computing vision

2.2 Classical infrastructures

Infrastructures have long been one of the most significant tools for boosting productivity and stimulating growth [13–16]. In fact, studies about the returns on investment (RoI) in successful infrastructure projects showed a 30–40% RoI for telecommunication infrastructures, more than 40% RoI for electricity generation, and more than 80% RoI for roads. It has to be noted that RoI tends to be higher in low-income countries than in middle-income countries [16]. Yet, it seems that the developing countries are lagging behind in both classical infrastructures and e-infrastructures.

However, as learned from classical infrastructures (e.g., electricity grids, telephone networks, and Internet), the long-run development of e-infrastructure should be undertaken with the following principles in mind:

1. Infrastructures benefit the public: In general, infrastructures are considered essential for the public. As a public good, infrastructures frequently have two essential properties [17]: non-excludability and non-rivalry. Non-excludability means that it is either impossible or prohibitively costly to exclude those who do not pay for the good when consuming it. The non-rivalry property implies that any person's consumption of the public good has no effect on the amount of its availability for others [18].

However, the Internet and computing e-infrastructures are not considered to be a public good by all scholars. In fact, while some scholars consider Internet a public good [19, 20], others see it as a club good since access to these infrastructure is restricted (i.e., since access charges have to be paid). A similar line of argument can be applied to computing e-infrastructures but with stronger restrictions of access than for the Internet (see section 3.2).

2. Infrastructures are ubiquitous: Infrastructures are huge in size, involve a large number of stakeholders (e.g., manufacturers, service providers, users, and regulators) and are used by the majority in society for each aspect of daily life (e.g., work, entertainment) [21].

The Internet, for instance, has a massive reach and realizes benefits in diverse communities, leading to create, expand, and improve businesses and leisure time of individuals. In the case of computing e-infrastructures, although they involve large number of (research) communities and are gradually opening and contributing to societal welfare, they are still limited in size and reach by the general public and businesses.

3. Infrastructures are sustainable: Sustainability is often set within a life cycle perspective, ranging from program development, implementation, evaluation, maintenance, and sometimes dissemination to other beneficiaries [22, 23]. Consequently, a sustainable computing e-infrastructure is an infrastructure that bears a stable, long-term funding (self-funding) and is capable of generating continuous developments and improvements [6, 24, 25]. It has been observed that lack of funding was the major threat to project sustainability [24, 26].

According to Voss et al. [6], computing e-infrastructure provisioning needs to become independent of governmental funding streams. If e-infrastructures can create value for a large number of people, it will allow establishing business models that generate revenue for their own long-term provisioning. Although e-infrastructure communities such as BELIEF and SEE-GRID acknowledge this as a key objective, sustainability remains a main challenge yet.

Concluding, a transition from the current computing e-infrastructures to public, ubiquitous, and sustainable e-infrastructures raises important concerns about funding models, management structures, governance, as well as potential ways of transitioning to the next computing e-infrastructure development phase.

2.3 Interconnection technology for e-infrastructures

While grid computing research has long addressed resource sharing within a distributed system and has managed to make notable progress, the interconnection of computing grids, which are under different ownership, has not been the focus until recently. While many scholars suggested pure technical solutions (i.e., the use of grid middleware (e.g., gLite, globus, Condor, GridBus, GOS) for interconnecting grid computing systems), others suggested approaches that take into account the economic aspects of interconnection of computing e-infrastructures. Economics aspects are essential since grid systems are owned by different entities with different objectives. These approaches range from scheduling algorithms across grid systems, interconnection gateway architectures, to service level agreement (SLA)-based coordination mechanisms.

Iosup et al. [27] propose a mechanism that temporarily binds computing grids from a remote computing environment to a local one, using decentralized decision-making mechanisms. The work by Rao and Huh introduces a probabilistic and adaptive scheduling algorithm for inter-grid resource sharing, using job estimates to predict the job scheduling feasibility on the target system [1]. A comparison between different grid resource provisioning mechanisms was presented by Assunção and Buyya [28]. In their study, they also evaluate the performance of different allocation policies in multiple-grid environments.

In the work of Wang et al. [2], an interoperability solution, which has been adopted by the EUChinaGRID project, has been suggested. It interconnects the EGEE infrastructure and the CNGRID e-infrastructures though a gateway, making gLite and GOS grid middleware interoperable. Another work by Assunção et al. introduces a gateway architecture [29], which mediates resource exchanges between grids. Wang and Jie propose another layer on top of grid middleware called HEAVEN (Hosting European Application Virtual Environment), in order to create a Virtual Private Computing Environment [4]. Finally, a great deal of work is undertaken by the Grid Interoperability Now community group [30, 31], which has been working on interoperability between grids to support job submissions, secure submission, and data transfers.

With respect to economic-related research, Ranjan et al. as well as Quan et al. propose an SLA-based coordination mechanism, in which a Grid Federation Agent is responsible for scheduling jobs across computing systems [3, 32]. Another relevant work by Quan et al. used brokered leases for sharing networked resources, where grids sites can register their offerings with brokers and, then, can acquire resources from these brokers by leasing them for a specified time [33, 34].

However, although these solutions acknowledge the necessity of considering the interconnection of computing grids from the perspective of different economically independent entities, these solutions do not consider the impact of funding and governance of those infrastructures.

3 Case study analyses of e-infrastructure projects with respect to funding and governance

To understand how e-infrastructures are financed, utilized, and managed, we analyze a set of 12 major e-infrastructure projects that represent well-recognized international and national e-infrastructure projects (Table 1 and Appendix).

3.1 Project funding

The communication networks that interconnect different local computing resources are either publicly or privately financed by companies. However, the main funding sources of international interconnections are essentially international organizations, donors, and public agencies, and research and development (R&D) support agencies. These grants are short-term contracts with a runtime of 2 years in average. Therefore, almost all of these infrastructure projects had to repeatedly request supplementary support grants to continue operating, administrating, and maintaining the e-infrastructure. Although this process has some advantages (as, for example, the tight monitoring of the development and the progress of the project), it also comes with considerable overhead costs (such as the costs incurred by reapplying for grants and by going through the re-evaluation process) for both researchers and funding organizations, which not only decreases the efficiency but also put these projects at jeopardy. In order to overcome this and create self-sustainable projects, some of the e-infrastructures (e.g., DFN and DEISA) introduced a membership-fee business model, seeking to cover the operational and upgrade costs, and to secure continuous, long-term revenues. According to DFN, this member-fee business model helped the network to compensate for reduced, direct government support and to decrease the dependency on grants. However, whether this business model has the potential to fully meet the financial requirements of computing e-infrastructures in the long run is yet to be tested, since, to date, these infrastructures rely mainly on research grants.

Surprisingly, despite the success of many private and public–private-partnerships (PPP) models in infrastructures development (e.g., toll roads, bridges, and railroads [13, 35]), the involvement of the private sector in computing e-infrastructure development activities is very weak. There is very little support for companies to use computing e-infrastructures, and there is also very little support for computing e-infrastructures from non-participating companies. Only EGEE and DEISA show bold signs of increasing involvement of industry stakeholders in their computing e-infrastructure development activities. This fosters knowledge transfer and increases understanding between research and industry.

3.2 Governance

For all projects studied, the computing e-infrastructures were always composed of two layers of networks. The lower network layer represents independent, local computing e-infrastructures belonging to different organizations or countries (i.e., different domains). The second network layer represents the higher layer, which is composed of multiple computing e-infrastructure of the lower layer. The investigated, higher-layer computing e-infrastructures varied in size and reach, ranging from six to 400 lower-layer computing e-infrastructure networks of various domains.

Although computing e-infrastructure projects had different management structures (i.e., decision-making bodies and processes), the management and operation responsibilities are divided between these two layers. The access to the lower-layer networks was managed by the holding organization of the e-infrastructure, while, at the inter-domain e-infrastructure level, the operation and management activities were undertaken by the corresponding project committee. The lower-layer holding organizations also oversee the operations and

Table 1 Major e-infrastructure case study projects

Project acronym	Name of e-Infrastructure project	Country	Start date
EGEE (1, 2, and 3)	Enabling Grids for e-Science	EU	2004
DEISA (1 and 2)	Distributed European Infrastructure for Supercomputing Applications	EU	2002
GÉANT (1 and 2)	European Gigabit Research and Education Network	EU	2000
DFN	Deutsches Forschungsnetzwerk (German National Research and Education Network)	Germany	1984
TeraGrid	Distributed Cyberinfrastructure for Scientific Research	USA	2001
NAREGI	National Research Grid Initiative	Japan	2003
K*Grid	Korea National Grid Infrastructure	Korea	2002
CANARIE	Canadian Advanced Network and Research for Industry and Education	Canada	1993
D4Science	Distributed col-Laboratories Infrastructure on Grid-Enabled Technology for Science.	EU	2008
EELA (1 and 2)	E-Science Grid for Europe and Latin America	Europe and Latin America	2006
BALTICGRID (1 and 2)	Baltic Grid Project	EU and Baltic	2005
SEE-GRID (1 and 2)	South-East Europe Grid-Enabled e-Infrastructure Development	EU and South-East Europe	2004

Another table of 60 additional smaller projects on computing e-infrastructure is available on request

govern the local network, whereas the higher-layer project committees oversee inter-domain issues such as contribution policies, resource sharing mechanisms, resource coordination, job priority settings, technical support, and accounting activities for all participating lower-layer networks. Despite this sophisticated management structure, governance and management activities on both layers are mainly carried out by research communities, who do not base their decisions on business practices. It limits business involvement and a potential transition towards a more open resource allocation scheme.

A standard request for access to the e-infrastructure resource from a project member institution starts with submitting a research proposal from a researcher of a (virtual) organization VO (see circled no. 1 of Fig. 2). At the next step (step no. 2), the proposal goes through a technical validation by science and technology committees of the local holding organization. If the proposal has been approved locally, the request for access is forwarded to the e-infrastructure project committee (step no. 3). At this higher-layer e-infrastructure, this proposal goes through a couple of screenings by technical committees and the executive committee. If the proposal gets all approvals and the local network has sufficient resource credits for executing the request, a certificate for access is issued (step no. 4), and the allocation of resources will be performed (step no. 5). Finally, the application can be executed on the computing e-infrastructure (step no. 6). The duration of such a process varies from days to months, depending on the proposal characteristics (i.e., purpose, period, and organization type of the organization submitting the proposal), availability of resources, and the frequency of committee meetings.

Most e-infrastructure projects do not allow any non-member organizations access to their e-infrastructures resources, independent to whether the non-member organizations are public, private, or research organizations. The only exceptions are the e-infrastructure projects DEISA and EGEE. Their e-infrastructure governance policies foresee non-member access. However, depending on the organization type and the purpose of use, the approval procedures of non-member requests are even more complicated. The use charges are based on metered usage of the computing resources (i.e., number of computing resources and duration). Tables 2 and 3 show the resource contribution policies, the resource sharing mechanisms, and the member and non-member access policies of EGEE and DEISA in detail.

4 Infrastructure development: a comparison with classical infrastructures

Historically, most classical infrastructure development activities (construction, operation, management, governance, and maintenance) were undertaken by the public sector. For this, governments used various funding models for the development of these infrastructures (e.g., direct capital investments from public budget, issuing bonds, direct borrowing, discounted loans, and private equity) [36, 37].

However, this has not been the case for all infrastructures. For instance, the fixed phone network in USA, the current UK railroad infrastructures, and the nineteenth century Dutch railroad network was financed, built, owned, and operated by the private sector. The reasons range from low performance of state-owned utilities [38], budgetary vulnerability [36], the low efficacy of public finance [13], and the proven private sector efficiency [35].

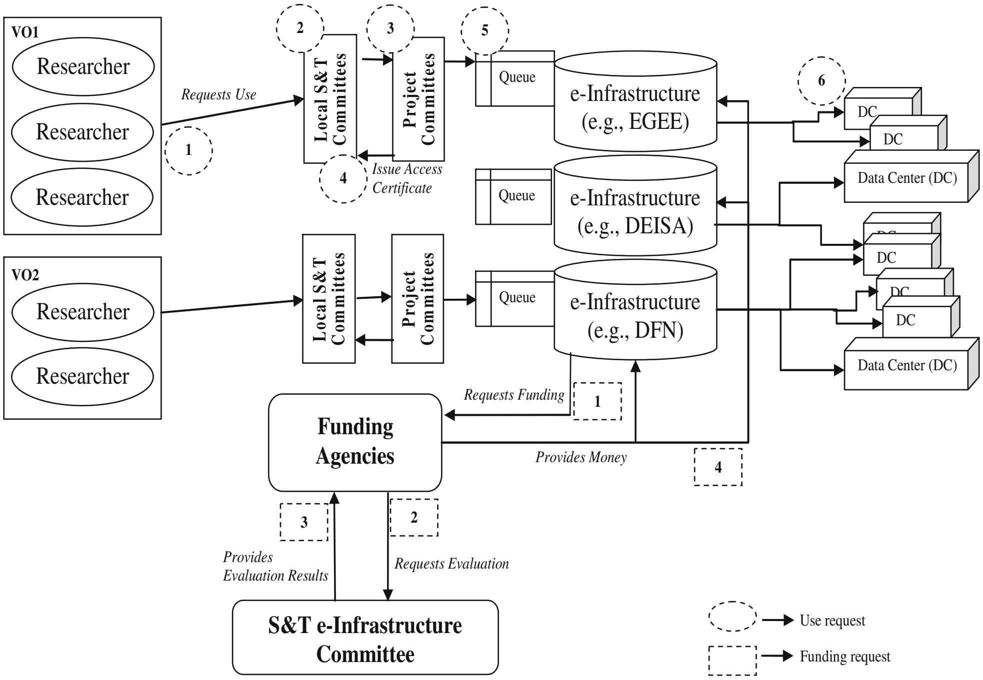

Fig. 2 Workflow applied for determining access to e-infrastructures

In general, governments tend more and more to contract infrastructure development activities to the private sector, reducing uncertainty and risks of long pay-back periods that are inherent to infrastructure investments. In order to achieve that, governments use different incentive and support mechanisms to motivate the private sector's involvement. By increasing private sector involvement, many infrastructure projects were able to create financial viability that fulfilled their operational and developmental needs (e.g., Internet). Nowadays, many infrastructure development activities are carried out by the private sector solely or under some form of PPP model (e.g., the Dartford Bridge, the Mont Blanc tunnel, and India National Highway Development Program). Although these approaches demonstrate a notable success, monopolist behavior and power disputes of private entities required the involvement of the government, introducing regulations or taking over operations in some cases [35].

Table 2 EGEE policies for resource contributions, member and non-member access, as well as the resource sharing mechanisms

Project	Contribution policy	Resource sharing mechanism	Member access policy	Non-member access policy
EGEE (1, 2, and 3)	For a virtual organization (VO), its contribution must be equivalent to its average consumption. Contributions can come from providers in all fields of science. In particular, they can come from national, regional computing centers, and networks or from the EU research network GÉANT	First, VO has to contact the Regional Operations Centre (ROC) in its region and define the minimum requirements expected of a site, and some operational requirements. Second, VO is expected to integrate computational resources into the EGEE infrastructure, generally equivalent to its average consumption (can be relaxed in exceptional circumstances).	First, access proposals have to be submitted to representatives of a specific research community. Second, these representatives submit the proposal to an EGEE Generic Applications Advisory Panel (EGAAP). Third, EGAAP makes recommendations to the EGEE Project Executive Board. Fourth, successful applicants receive an access certificate and support for adapting their scientific software to the EGEE grid.	First, a non-member has to join an existing virtual organization which is already a member and takes responsibility. Second, the non-member gets an access certificate by following the procedures for a member.

Table 3 DEISA policies for resource contributions, member and non-member access, as well as the resource sharing mechanisms

Project	Contribution policy	Resource sharing mechanism	Member access policy	Non-member access policy
DEISA (1 and 2)	Each partner has to contribute a fraction of its computing resources (in general, more than 10%).	Basic principle of resource exchange is that all partners can use as much as they had contributed.	First, validation of access proposal by national evaluation committees. Second, technical validation of the proposal by the DEISA technical teams. Third, approval of DEISA Executive Committee. Fourth, access is granted, following the use priorities of the consortium.	First, DEISA Consortium accepts paid access to computing resources by external industrial users. Second, DEISA partners dedicate (at most up to 3%) for external users. Three, free access can be granted to a limited number of scientists from third party European countries and not members of DEISA.

4.1 Cable-based infrastructures

Based on our previous discussions and the case study analyses, we compare the current computing e-infrastructure development paths with three cable-based, classical infrastructure development paths. These classical infrastructures are the electrical grid, fixed phone network, and the Internet. The analysis of the development paths of infrastructures can offer very valuable lessons. The development paths are examined with respect to funding, user profile, access, technology, and economics. Table 4 shows in detail the differences in the development paths of the three classical infrastructures and the computing e-infrastructure. The character "→", which is used in the table, indicates a transition from one development phase to another.

As can be seen in Table 3, although all of these infrastructures (except for the USA telephone network) relied on public funding in their early stages, a diversification of funding resources and the creation of sustainable funding models has been achieved in later stages. This came mainly as a result of privatization and the application of business practices. For instance, the Internet, which is most similar to computing e-infrastructures, achieved a wide adoption through private sector investments and business models around new network service offerings. Therefore, the market structure changed and became more competitive.

While the electrical grid, the telephone network, and the Internet are now open (i.e., accessible by all users), computing e-infrastructure access is still limited. The access is exclusive to specific communities of researchers only. The Internet, which was created by and for researchers in the beginning as well, was made available for business and the general public later on. The electrical grid and the telephone network were targeted at the public from the very beginning.

Although some might argue that the technology level offered by computing e-infrastructures is much higher than other infrastructures, the technology level of the classical infrastructures that we consider here was also considered to be high in their early days.

With respect to the interconnection structure, all of these infrastructures, including computing e-infrastructures, started as a number of independent systems, which got interconnected in a later stage. Some of those infrastructures became, in the next stage, multiple interconnected systems, existing in parallel to other multiple interconnected systems. Other infrastructures (e.g., telephone network and Internet) became networks of systems (i.e., the Internet is a network of networks). The structure of the computing e-infrastructure is currently only a network of interconnected systems.

In addition to this, two more aspects of interconnection can be considered: interconnection with respect to the technological capability and interconnection with respect to economic incentives to interconnect. Regarding the first, the electrical power network and the Internet were open from the beginning. For the telephone network, openness was achieved through the introduction of standardized connectors. In a similar way, the openness of the computing e-infrastructure came through the development of adaptors that can transfer data format of one middleware into the data format of another middleware.

From the economic perspective, openness of the electrical power network and the telephone network could only be achieved through regulation. Those two networks are considered natural monopolies. Although the Internet shows the same characteristics, it is, due to its development process, currently an open infrastructure without any regulation. The computing e-infrastructure is still in its early stage, in which the access to the resources is still controlled.

Finally, the security and dependability of all four infrastructures is already high, although significant investment in research is being undertaken to improve the security and dependability of these infrastructures, protecting it against significant failures in case of criminal and terror attacks.

Table 4 Differences in the development phases of three classical infrastructures and the computing e-infrastructure

Aspects of infrastructures	Electrical power grid	Fixed phone	Internet	Computing e-Infrastructure
Funding source	Public→private	Public → public–private→private (worldwide, except for USA, where the funding source has been private)	Public → private	Public
Funding schemes	Tax → pay-per-use and special tax	Tax → fixed rate plus pay-per-use	Public grants → pay-per-use	Public grants
Market structure	Different based on level: 1. Power generation: monopolies → oligopolies 2. Power distribution: monopolies → oligopolies → partial competition 3. Transmission lines:	Monopolies →Partial competition	Different based on level: 1. Backbone: monopolies → oligopolies 2. Tier2 and tier3 networks: monopolies → oligopolies → partial competition	Monopolies
User access to infrastructure	Open	Open	Exclusive → open	Exclusive
Target users	Public	Public (although the first telephones were shared between a group of people)	Research → Business → public	Research
Technology level offered	Low → high	Low → high	High → very high	Very high
Interconnection structure of the infrastructure	Systems → multiple systems	Systems → network	Systems → multiple systems → network	Systems → multiple systems
Interconnection with respect to user technology	Open	Closed → open since standardized telephone connectors exist	Open, because of the existence of standards from the beginning	Closed → pen since middleware adaptors exist
Interconnection with respect to economics	Closed (geographic monopolies) → open through regulation (separation between transmission networks, distribution networks and generation; e.g., households can connect to the power grid)	Closed → open through regulation	Closed for industry → open	Closed since only certain researchers have access
Security	Low → high	Low → high	Low → high → very high	High
Dependability	Low → high	Low → high	High → very high	Low→high

4.2 Lessons learned

Based on the results from the comparison of the development paths, literature on classical infrastructures, and our case studies of computing e-infrastructures, there are a few lessons to be learned.

First, funding e-infrastructures development through short-term grants tends to be inefficient and insufficient. All e-infrastructures studied required additional funding in later stages, and many of them will even require more in the future. This limits long-term planning and creates additional cost for both donors and researchers of those infrastructures.

Second, while previous infrastructure development literature suggests private sector involvement and adoption of business practices, our case study analyses of the computing e-infrastructure show a weak tendency toward both of these practices. An explanation can be found in two facts. On the one hand, computing e-infrastructures are still publicly funded, posing restrictions on private use of public research resources. As a consequence, the potential of the private sector is not tapped, missing out on the private sector's knowledge on technology transfer, its huge investment capacity, and its creativity for finding sustainable business models as it did with the Internet. On the other hand, computing e-infrastructures are mainly governed by researchers, who are more concerned about scientific and technological issues than business practices (i.e., an economically efficient use of resources). As a consequence of this lack of business practices, further obstacles are imposed on opening these computing resources to a larger base of users within academia and industry.

Finally, the complexity of access approval procedures is creating an extra barrier for researchers and businesses. Current standard access procedures of many e-infrastructures are restricted to members, require users to wait in long request queues, and require approvals for requests from many different committees. Since we believe that e-infrastructures should be opened in similar ways as the Internet, current access approval procedures need to adapt business-oriented practices, laying the foundation for an Internet-like infrastructure.

5 The proposed market-based funding model for computing e-infrastructures

5.1 Token-based mechanisms

The token-based system that we use for our funding model is based on the work of many scholars suggesting the use of token-based market mechanism in the area of P2P and grid computing. In particular, these scholars address the aspects of accounting systems, implementations of incentive systems, and token-based system designs.

With respect to accounting, Barmouta and Buyya propose the grid accounting system Gridbank that can manage tokens. Tokens are exchanged in return of grid services [39]. Liebau et al. propose a token-based accounting system for P2P systems that is called TbAS [40]. Within this system, tokens not only have a fixed value but also serve as a receipt of payment. Hausheer suggested another token-based accounting mechanism to incite users to share valuable content and to efficiently balance requests among all participating peers [41].

Another set of work mainly addresses the issue of incentives for participating in sharing resources [42, 43]. In this context, Anandasivam et al. propose an incentive mechanism called Token Exchange System (TES) for the grid computing e-infrastructure community [42]. TES tokens can be issued and distributed by the participants themselves. The value of the token is derived from the reputation of a participant and the number of issued tokens. Wongrujira and Seneviratne also used tokens for accounting of the behavior of peers within a P2P system [43].

The description of token systems has been addressed in [44–46]. Cohen et al. uses electronically signed tokens that are issued to the clients by the computing grid e-infrastructure as a ticket of entry and a payment confirmation [44]. They can be used after the service operation has been invoked and before the expiry time. Vishnumurthy et al. suggest the payment framework KARMA for P2P systems using tokens for exchanging resource [45]. The MMAPPS Consortium presents a system in which peers exchange tokens (in forms of receipts, invoices, or currency) of a value equal to their consumption of resources [46]. Hereby, the MMAPPS system distinguishes three types of tokens: tokens issued by an external bank, tokens issued by an internal bank, and tokens issued by each peer.

Although these works on token-based mechanisms cover a wide range of aspects of token-based systems, they do not take into consideration the money flow between different stakeholders of such a system. In particular, they do not focus on the money flow within computing e-infrastructures.

5.2 The sustainable funding model

Based on the analysis results of the previous sections, a new funding and governance model for computing e-infrastructure is proposed. By applying this model, computing e-infrastructure providers can sell their resources to researchers and companies on demand.

The details of this model are shown in Fig. 3. Under this model, a researcher requests access from the S&T e-Infrastructure Committee. Based on the policies for proposal evaluation and resource availability of the committee (note, there is no difference to the currently applied procedures), the committee either rejects the proposal or issues a certain

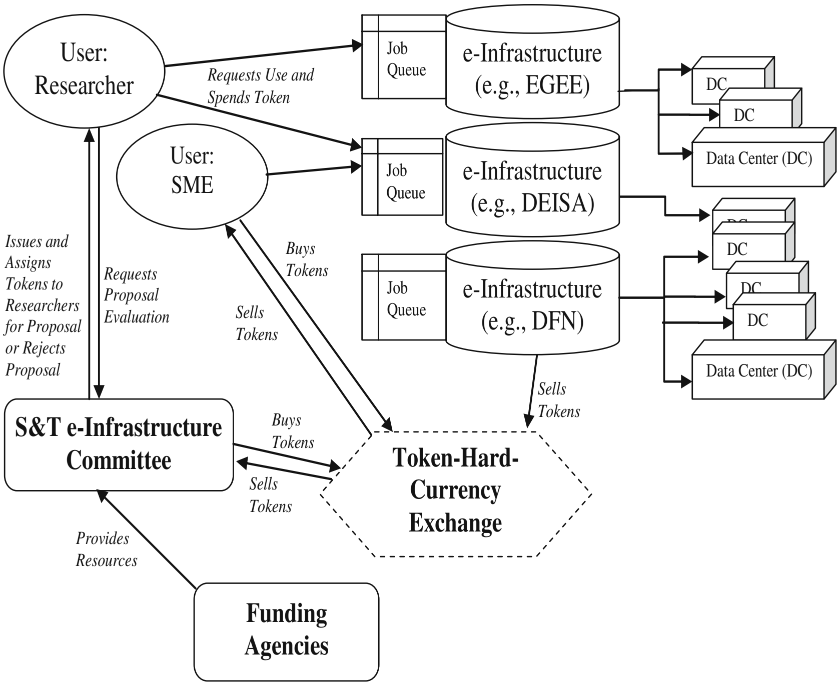

Fig. 3 Proposed model for simpler access to computing resources and sustainable funding of computing e-infrastructures

number of tokens such that the researcher can perform the work outlined in the proposal. The tokens represent a certain monetary value, which the researcher can only use for buying resources at participating computing e-infrastructure providers. Then the user searches for an appropriate e-infrastructure that can fulfill his demand at an acceptable price. Once an appropriate e-infrastructure has been found, the user joins the corresponding queue and pays for the execution of his job with the tokens. This procedure gives the user the flexibility to find the best-fitting resources and prioritize his work. It also helps resolving preference differences among researchers. The system gives priority to the researcher, who is willing to pay more tokens. For the computing e-infrastructure providers, this kind of model can help them to balance workload, maximize utilization, and attract users through good services (e.g., low waiting times or quick support services).

At the token–hard-currency exchange, companies can buy and sell tokens according to their resource needs. Computing e-infrastructure providers use it to sell their earned tokens. They use the revenue to maintain and upgrade their infrastructure. In the same way, the S&T e-Infrastructure Committee buys tokens at the exchange, based on the funding from a funding agency. The setting of the exchange rate between tokens and real world currencies should follow market principles as well. However, this is subject to further research in the area of computational markets.

The main advantages of the proposed model is that it allows users to prioritize their jobs on the computing e-infrastructure, opening new funding streams from companies in need of large processing power for a short time period, increasing economical efficiency and resource utilization of available resources, balancing workload between different computing e-infrastructures, and providing simplified access procedures to computing resources. Consequently, it creates a proper transition to market-oriented practices in the governance of computing e-infrastructures.

Despite these advantages, this model comes with a few requirements, which have to be fulfilled. This model requires the existence of additional support services that have to be offered and maintained. For example, the currency exchange has to be managed, token accounting systems have to be installed, and payment systems have to be established. In addition to this, this model increases competition for existing commercial utility computing offerings (e.g., Amazon EC2), which has to be addressed in order not to disturb the emerging market in computing resources.

5.3 Rationality for a market-based approach

The motivation for the suggested funding model originated from four issues with current governance and funding models of computing e-infrastructures. Those issues are the economically inefficient resource allocation, the missing interconnection of computing e-infrastructures, the inefficient long-term capacity planning, and the restricted access to the computing resources.

1. Economically efficient allocation of resources

The first issue is the economically inefficient allocation of computing resources. The main allocation mechanism (with slight variations), which is currently applied by publically funded computing centers, is the first-come-first-serve (FCFS) mechanism.

Economically efficient mechanisms (or utility-based mechanisms) instead allocate resources to those users with the highest need, therefore making best use of limited computing resources. They also generate additional revenue under congestion, which can be used for upgrading the existing e-infrastructure, so that more people can be served, and the congestion is reduced. Literature comprises a substantial set of mechanisms on economically efficient resource allocation [47–50].

To illustrate the difference in overall user utility gained from those two allocation mechanisms, we simulate both resource allocation mechanisms within one computing e-infrastructure. In detail, Fig. 4 shows the user utility gained with the FCFS allocation mechanism, the utility of any allocation mechanisms if the capacity is unlimited (i.e., supply is higher than demand) and the utility gained with an economically efficient allocation mechanism.

In case of the no-capacity-limit allocation mechanism, we assume an imaginary situation in which the infrastructure has unlimited capacity, and all user demand can be satisfied. Under these prerequisites, the type of resource allocation mechanism is not important. In the case of FCFS resource allocation mechanism and the utility-based resource allocation mechanism, only a limited number of user jobs can be fulfilled through the available capacity.

For our simulation, we assumed that a user job always consumes one unit of available infrastructure resources. Furthermore, we assumed a computing e-infrastructure capacity of 300 units per time slot (i.e., jobs of 300 users can be served without rejecting any user job). The incoming user jobs are equally distributed with respect to the users' valuation of the resources (i.e., user utility). For the FCFS mechanism, the jobs are executed in random order. For the economically efficient mechanism, the jobs with the highest utility are served while the low utility jobs are delayed to the next time slot.

The net user utility that we measure is defined as the user utility UU_i minus the cost C (i.e., waiting time until the job gets served). C is zero for jobs that get served. If a job does not get served, the utility $UU_i=0$ and the cost $C=1$. Based on these definitions, the overall utility UI_j of an infrastructure j with n users can be calculated as follows:

$$UI_j = \sum_{i=1}^{n} UU_i - C \tag{1}$$

Equation 1 states that the utility of one computing e-infrastructure UI_j is the accumulated net utility of all users i on infrastructure j.

The network utility UN is the sum of all utilities accumulated on all infrastructures j with $1 \leq j \leq m$. This is expressed with the following formula:

$$UN = \sum_{j=1}^{m} UIj \tag{2}$$

whereas the parameter m represents the number of computing e-infrastructures.

The measurements shown in Fig. 4 illustrate that the allocation of resources based on user utility generates a significantly higher economic efficiency than the FCFS resource allocation mechanism if the number of users is larger than 300. If the number of users is 700, the difference in utility is 810 units. At that point, the utility of the utility-

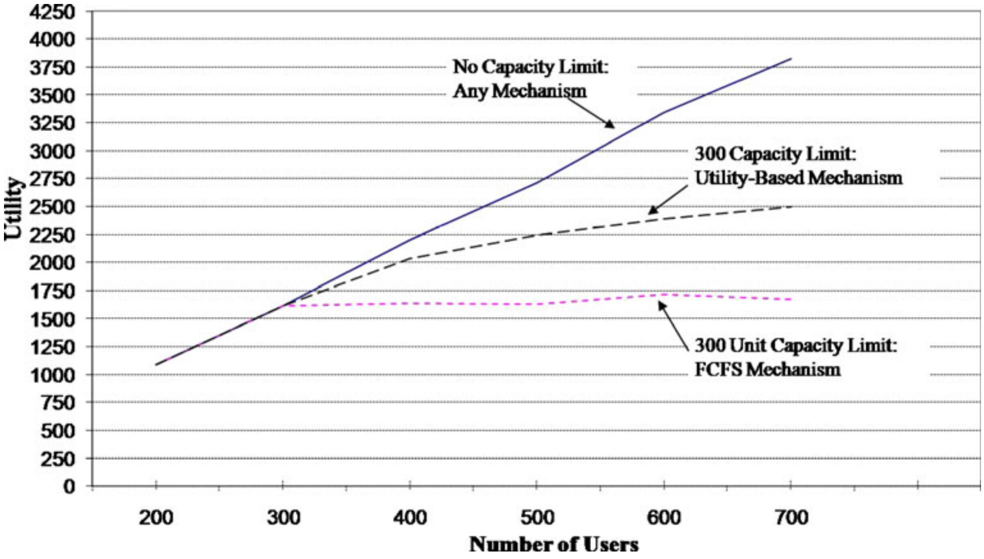

Fig. 4 User utility for three resource allocation mechanisms: any mechanism if no capacity limit exists, the economically efficient (utility-based) mechanism, and the FCFS mechanism

based mechanism is 2,500 units while the utility of the FCFS mechanism is only 1,690 units.

The proposed market-based funding scheme allows implementing utility-based resource allocation and, therefore, would achieve a higher economic efficiency than existing ones.

2. Interconnection of systems

The second issue rises from e-infrastructures that are not interconnected. In fact, many computing e-infrastructures of different capacities and capabilities exist worldwide. They are still stand-alone systems, not part of a network of computing e-infrastructures. Due to their geographical distribution, resource differences, and access policies, the demand on each of these computing e-infrastructures differs over time. Consequently, at some points in time, some of these e-infrastructures will be working at their full capacity while others will be underutilized.

This shortcoming can be resolved by connecting these systems through interconnection middleware (section 2.3). If those e-infrastructures are interconnected, spare capacity and demand can be balanced between those systems. Consequently, it leads to more efficient utilization of computing resources. Figure 5 shows an example of this situation, illustrating the gain in utility by interconnecting two computing e-infrastructures. For our simulation, we used the same setup as described in the previous section. In particular, we used the utility-based resource allocation mechanism.

Figure 5 shows that the interconnected e-infrastructures (upper curve) working as one infrastructure achieve a higher network utility *NS* than two computing e-infrastructures working separately (lower curve). Although the difference is not significant, this inefficiency can represent high losses, if we consider supercomputing e-infrastructures.

3. Long-term capacity planning

The third issue comes from inefficient, long-term capacity planning. Although a lot of work on capacity planning and forecasting of demand have been undertaken, the values of input factors that determine demand are still difficult to predict. The input factors can be the number of users, the number of available resources, the price of individual resources, the size of infrastructures, the support service costs, the market structure, the funding amount, and the funding time. Because of the difficulty in predicting the demand for computing resources, gaps between demand and supply will always emerge. Figure 6 illustrates the resulting inefficiencies in long-term capacity planning. The inefficiency is indicated through two gray areas, labeled *C1* and *C2*.

These inefficiencies are of two types. The first one is caused by supply surplus *C1*:

$$C1 = \int_{t=0}^{tc} (S(t) - D(t))dt \tag{3}$$

The second type of inefficiency comes from demand surplus *C2*:

$$C2 = \int_{t=tc}^{f} (D(t) - S(t))dt \tag{4}$$

In Eqs. 3 and 4, t represents time, starting from $t=0$ (i.e., project start) to $t=f$ (i.e., project end). tc is the time when supply equals demand (i.e., when the available computing resources are equal to all incoming jobs).

Assuming one funding period only, the funding is assumed to be spend for a fixed amount of supply $S(t)=sc$. For this, the supply S has been set such that it minimizes inefficiencies (i.e., the sum of *C1* and *C2*).

In the example of Fig. 6, the actual demand $D(t)$ is represented as a linear function $D(t)=bt+c$, where b describes the increase in demand over time and c, the initial demand.

Since the current government funding schemes of computing infrastructures only allow one-time funding schemes, inefficiencies as shown in Fig. 6 emerge.

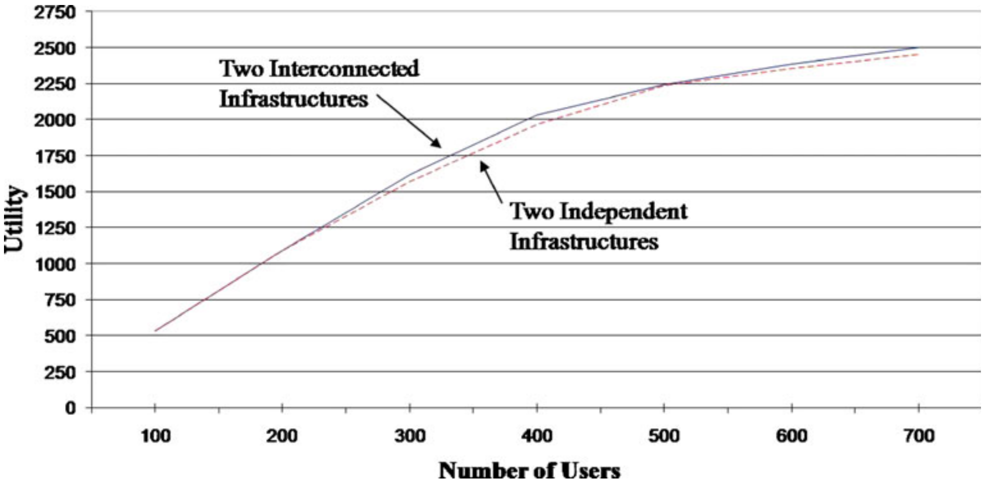

Fig. 5 Comparison of the utility of two interconnected computing e-Infrastructures and the sum of utilities of two separate computing e-Infrastructures

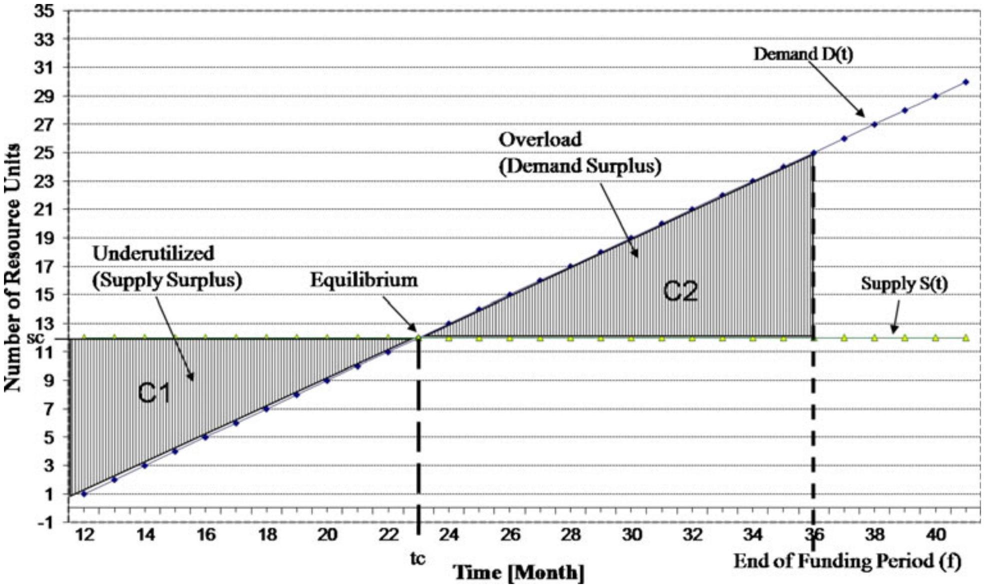

Fig. 6 Example for the inefficiencies of long-term investments

Moreover, these inefficiencies are at risk of getting larger, if computing e-infrastructure projects have to rely on repeated rounds of government funding. In this case, the inaccuracy of capacity planning can increase through the uncertainty about the funding amount and the funding time.

Since these two factors have not been considered in literature thoroughly, we analyze the inefficiency that results from variations of those factors in more detail. Figure 7 illustrates the inefficiency due to delayed funding and due to a funding amount that is lower than planned.

In Fig. 7, the inefficiency caused by a lower-than-planned funding amount can be calculated by subtracting area *C3* from area *C4*. Both areas lie between the actual supply *S*(*t*) and the planned supply *S'*(*t*). *C3* represents lower loss due to less supply surplus. *C4* denotes the demand that cannot be covered with a low funding amount. In general, this area is defined as shown in Eq. 5:

$$C4 - C3 = \left(\int_{t=tc}^{f'} (D(t) - S(t))dt - \int_{t=tc'}^{f'} (D(t) - S'(t))dt\right) - \left(\int_{t=0}^{tc'} (S'(t) - D(t))dt - \int_{t=0}^{tc} (S(t) - D(t))dt\right) \tag{5}$$

Inefficiency due to delayed funding occurs if the funding is not provided on time. For example, if funding is delayed from time $t=0$ until time $t=tc$ (Fig. 7), then the computing

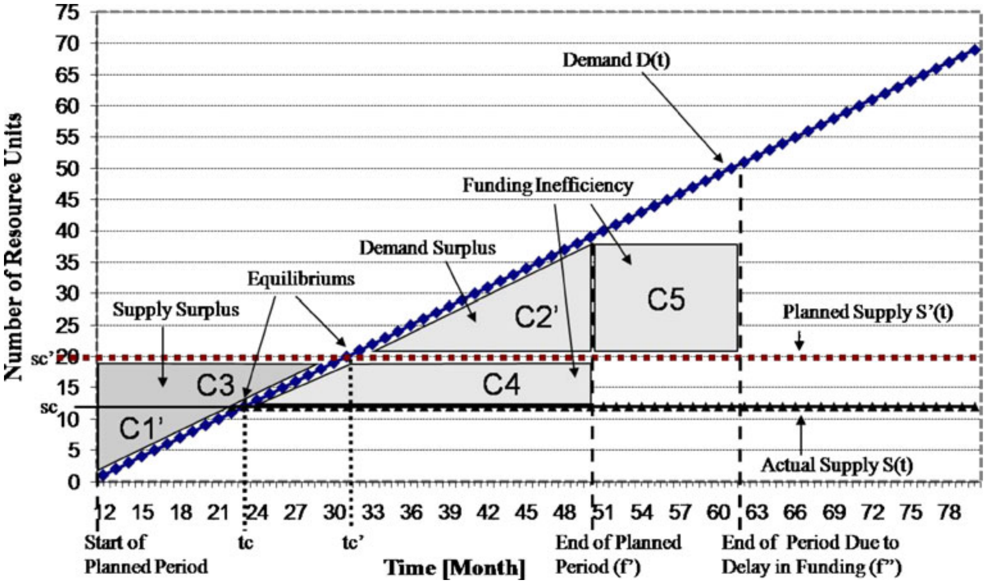

Fig. 7 Inefficiencies due to delayed funding (*C5*) and due to a funding amount that is lower than planned (*C4*–*C3*)

resource will be in use until time *f"* instead of *f'*. During that time interval, the demand for computing resources is much higher than during the time period from 0 to *tc*, resulting in a loss. This loss is indicated through the gray area labeled *C5* in Fig. 7. In general, the inefficiency is defined as:

$$C5 = \int_{t=f'}^{f''} (D(t) - S'(t))dt - \int_{t=0}^{tc} D(t)dt \qquad (6)$$

This calculation shows that inefficiencies due to delayed funding or due to lower-than-planned funding can be significant. Therefore, these causes for inaccurate capacity planning should be avoided. This would be possible by generating a constant revenue stream through the proposed market-based funding model.

4. User access

The fourth issue rises from excluding users from using computing e-infrastructures. The following classification of users, who are currently excluded from accessing computing resources, shows that this causes a loss in demand which could otherwise be used to further growth the computing e-infrastructure:

- Researchers, who lack sufficient resources at their own e-infrastructure organization and cannot gain access to more resources because of local access policies. For these users, a market-based access policy would help resolving preference differences between users of the same e-infrastructure.
- Researchers and businesses, which do not own or have access to computing e-infrastructure but have sufficient financial resources to buy access times from current computing e-infrastructures. In this case, the proposed market-based funding scheme for e-infrastructures would provide them with on-demand e-infrastructure services, putting them at the same level as local researchers.
- Users, who have no financial resources to buy computing resources. For these users, the proposed model would not make any difference. However, international R&D collaboration programs could give these researchers grants in form of tokens that are usable at participating computing e-infrastructures. This would foster the worldwide collaboration between researchers.

The proposed token-based and market-based funding model allows all users, independent of their goals or origins, to access the computing e-infrastructure.

6 Analysis

6.1 Market implications

The analysis of the four issues of current computing e-infrastructures suggests that the proposed funding model can resolve those issues and can be a first step toward sustainable computing e-infrastructure. Sustainability is achieved by the fact that the usage of computing e-infrastructure services generates revenues based on the principles of demand and supply. The revenues can be used for maintaining and upgrading the existing computing e-infrastructures. Consequently, the overall capacity of computing resources increases, the cost of these resources decreases, and a large number of users can benefit from the improved availability of computing e-infrastructures in the long run.

The main differences between existing e-infrastructure funding models and our proposed funding model can be summarized as follows:

- Our proposed market-based funding model extends access to computing e-infrastructures by including researchers and companies not associated with any computing e-infrastructure organization.
- Our model is based on a market-oriented mechanism that allows new revenue streams to be exploited and maximizes the total utility of the computing e-infrastructure.
- Our model fosters growth and development of computing e-infrastructures by reducing four types of inefficiencies that are inherent to existing funding models.

6.2 Policy implications

Infrastructure development is a complicated task for policy makers, especially if services exist that are similar to future infrastructure services. Our literature review, our case studies, and our economic analyses identified three crucial policy issues that need to be resolved, in order to facilitate the transition from the current computing e-infrastructure to the vision of cloud computing.

First, since private sector involvement and business-oriented practices are important to infrastructure sustainability [13, 16, 35, 37, 38], incentives and policies should be created to encourage private sector participation and business-oriented governance for all e-infrastructure activities (i.e., funding, governance, and development). However, proper public policies and regulations that secure public interest need to be in place (especially, in an early stage, when an industry is not matured [51]). Such regulations will guarantee network neutrality and will attract a growing fraction of the population to use the e-infrastructure resources [52].

Second, as for all public infrastructures, access and use policies for computing e-infrastructures need to be relaxed. The basis can be a market-oriented mechanism for service provisioning. This will give users (researchers, companies, and in particular, SMEs) the flexibility to exchange and acquire services at low cost.

Finally, despite the economic challenges of expanding the boundaries of computing e-infrastructures, which have been presented in this paper, international interconnection of computing e-infrastructures and collaboration within multi-national projects will be a key to a worldwide, sustainable, public, and ubiquitous cloud computing vision.

7 Conclusion

This paper analyzed funding and governance practices of existing computing e-infrastructures. The result of this analysis was compared with similar classical infrastructures. The comparison showed that, while infrastructure literature suggests more business-oriented practice and increased private sector involvement, current computing e-infrastructures are still relying mainly on short-term public grants. Besides, the access and governance models are still exclusively in the hands of research communities. These two facts largely explain the limited evolution and limited mass adoption of these computing e-infrastructures.

To allow simple, flexible, and sustainable access to computing e-infrastructures, we proposed, analyzed, and discussed a market-oriented funding model. Although our funding model is the first step towards a sustainable, public, and ubiquitous cloud computing infrastructure, many other issues (e.g., pricing, accounting, service differentiation, competition, and market structure) need to be further investigated.

Finally, we need to emphasize that, despite the necessity of adopting business-oriented approaches for computing e-infrastructures, continuous collaborations between international, inter-sectoral (private and public), and inter-disciplinary organizations are key success factors for the transition towards the cloud computing era.

Appendix

Table 5 Funding and governance models of existing e-Infrastructure Projects

Project	Funding source	Governance		
		Composition	Management	Member access
DEISA (1 and 2) [54]	EC	Six partners	Executive Committee	Validation by national evaluation committees
		(National Research Networks)	National Evaluation Committee	Technical validation by DEISA technical teams
				Executive Committee of the consortium sets priorities
GÉANT (1 and 2) [55]	EC and the National Research and Education Networks (NREN) of EU countries	38 partners	Executive Committee	Access to GÉANT2 is only possible through a member NREN
		(32 European NRENs, DANTE and TERENA; and four Associate NRENs)	Policy Committee	Contact GÉANT consortium, which verifies the eligibility of proposal
			Project Coordinator	
			Technical management committee	
DFN [56]	Federal Ministry of Education and Research of Germany and differentiated membership fee	400 partners (universities, technical colleges, research labs of companies, government agencies)	Executive Office	Users must belong to one of the member organizations
				Paid access is allowed based on resource availability and purpose
				Executive Office control operation, planning, organization, supervision, consultancy, finance, administration, and international contacts
TeraGrid [57]	National Science Foundation of USA	Nine partners (supercomputing resource providers)	System Management Group	Academic researchers have to provide an abstract describing the work to be done
			Grid Infrastructure Group	More extensive work involves a proposal that is reviewed during a quarterly peer-review process

Table 5 (continued)

Project	Funding source	Governance		
		Composition	Management	Member access
			Cyberinfrastructure User Advisory Committee	All allocation proposals are handled through principal investigators (PI), who must be a researcher or educator at an US-based institution
NAREGI [58]	Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT)	Thirteen partners (three universities and ten institutions)	Center for Grid Research and Development (National Institute of Informatics)	Project is operated by the center for Grid Research and Development It allows access through a use certificate only to joint research organizations or participating institution and organizations
K*Grid [59]	Ministry of Information and Communication of the Republic of Korea (MIC)	50 partners (universities, research institutes, and companies)	K*Grid Testbed Team	Users must belong to one of the member organizations of K*Grid or PRAGMA
			KISTI	User requests, which have to state the purpose for using K*Grid, are reviewed
CANARIE [60]	Membership fees, Government of Canada, and Industry Canada	85 partners	It is incorporated	Applications for interconnections have to go through GigaPoPs for regional networks
		(22 universities, others are companies and research centers)	Board of Directors (members are from companies, education and research communities) Network Policy Committee	Applications are reviewed by CANARIE in consultation with the Network Policy Committee
EGEE [53]	EC with significant contributions by project partners	140 partners	Administrative Federation Committee	Only members can access the resources
		(Research centers, universities, companies with approximately 300 sites in 52 countries)	Activity Management Board	A use certificate is needed to access the network
			Collaboration Board External Advisory Committee	The working of the network is checked by the different Technical Management Board
			Project Management Board	
			Technical Management Board	
EELA (1 and 2) [61]	EC and the National Research and Education Networks (NREN) of EU countries	50 partners	Project Coordinator	Only member have access
			Management Board	The project is open to any organization willing to collaborate
			Technical Coordinator	After members integrated computing resources into the EELA-2 Grid, they can run applications
			Technical Board And three more committees	The approval of a specific application requires the approval from different committees
BALTICGRID (1 and 2) [62]	EC and Baltic countries	Ten partners	Project Management Board Members A number of committees that oversee different operations	Members need to get a certificate, load the certificate into a browser, join a Virtual Organization, install the certificate on the user interface machine, and submit job and retrieve results
SEE-GRID (1 and 2) [63]	EC and south-eastern European countries	13 partners	Management Board	Members need to request access through NERNs
			Regional Operating Centers Further diverse committees	After joining a Virtual Organization, they get a certificate and can submit a job

Reference

1. Rao I, Huh EN (2008) A probabilistic and adaptive scheduling algorithm using system-generated predictions for inter-grid resource sharing. J Supercomput 45:185–204
2. Wang Y, Scardaci D, Yan B, Huang Y (2007) Interconnect EGEE and CNGRID e-infrastructures through interoperability between gLite and GOS middlewares. International Grid Interoperability and Interoperation Workshop (IGIIW 2007), e-Science conference, Bangalore, India
3. Ranjan R, Harwood A, Buyya R (2006) SLA-based coordinated superscheduling scheme for computational grids. IEEE International Conference on Cluster Computing, Barcelona, Spain
4. Wang L, Jie W (2009) Towards supporting multiple virtual private computing environments on computational grids. Adv Eng Softw 40:239–245
5. Hwang J, Altmann J, Bany Mohammed A (2009) Determinants of participation in global volunteer grids: a cross-country analysis. GECON 2009, Workshop on Grid Economics and Business Models. Springer LNCS, Delft, Netherlands
6. Voss A, Procter R, Hewitt T, Asgari-Targhi M, Daw M, Baun C, Gentzsch W (2007) Sustainability of e-infrastructures (for the social sciences). Third International Conference on e-Social Science. Ann Arbor, MI, USA
7. European Community (2006) e-Infrastructure: building blocks for the European research area. Official Publications of the European Communities, IST projects in the area of research networking and the members of the research infrastructure team of the European Commission
8. Hey T, De Roure D, Trefethen AE (2006) e-Infrastructure and e-Science. In: True visions: the emergence of ambient intelligence. Springer, Berlin Heidelberg
9. NSF Office of Cyberinfrastructure (2007) (Available at: http://www.nsf.gov/dir/index.jsp?org=OCI. Accessed on: 24/October/2007)
10. Hey T, Fox G (2005) Grids and Web services for e-Science. Concurrency Comput: Pract Ex 7(2–4):317–322
11. Reid A (2007) The new holy grail: An Australian e-infrastructure. EDUCAUSE Australasia. Melbourne, Australia. (Available at: http://www.caudit.edu.au/educauseaustralasia07/authors_papers/Reid-238.pdf)
12. Ford, R. (2007) Connection between cyberinfrastructure, bandwidth, and SCAUIDs. PowerPoint presentation, a briefing to the College of Health Professions and Biomedical Science (Available at: http://www.umt.edu/it/itorg/CIO/CyberInfrastructure.ppt)
13. Eichengreen B (1994) Financing infrastructure in developing countries: lessons from the railway age. Policy Research Working Paper 1379, background paper for world development report, The World Bank Office of the Vice President, Development Economics
14. Jones S (2004) Contribution of infrastructure to growth and poverty reduction in east Asia and the Pacific. Background paper, Oxford Policy Management
15. Kwon E (2000) A link between infrastructure, growth, and poverty in Indonesia. Stage 1 report, economics and development resource center, Asian Development Bank
16. Estache A (2004) Emerging infrastructure policy issues in developing countries: a survey of the recent economic literature. Background paper for October 2004 meeting of the POVNET Infrastructure Working Group
17. Samuelson PA (1954) The pure theory of public expenditure. Rev Econ Stat 36(4):387–389
18. Bezanson KA, Sagasti F (2001) Financing and providing global public goods: expectations and prospects. Development Financing 2000, Ministry of Foreign Affairs, Study 2001:2
19. Thorsteinsdóttir H, Daar AS, Smith R, Singer P (2003) Genomics—a global public good? Lancet 361(9361):891–892
20. Krishnan R, Smith MD, Telang R (2004) The economics of peer-to-peer networks. J Inform Tech Theor Appl 5(3):31–44
21. Calvo CM (1998) Options for managing and financing rural transport infrastructure. World Bank Technical Paper 411. Washington, DC, USA
22. Elkington J (1994) Towards the sustainable corporation: win–win–win business strategies for sustainable development. Calif Manage Rev 36(3):90–100
23. Scheirer MA (2005) Is sustainability possible? A review and commentary on empirical studies of program sustainability. Ame J Eval 26:320
24. Stambrook D (2006) Governance and funding of land transport infrastructure. Virtuosity Productions Inc. (Available at: http://www.uofaweb.ualberta.ca/ipe//pdfs/TransportPaper-Stambrook.pdf)
25. eIRG Group (2007) A sustainable grid infrastructure for Europe. Executive summary of the open workshop on e-Infrastructures, Heidelberg, Germany (download http://www.roadmaptgi.fr/Documents/Sustainable%20GRID%20infrastructure.pdf)
26. Frechtling J, Lockwood J, Silverstein G, Somers L, Tuss P (1999) Evaluation of the telecommunications and information infrastructure assistance program for the 1994 and 1995 Grant Years. Report prepared by US Department of Commerce, National Telecommunications and Information Administration. Washington, DC, USA
27. Iosup A, Epema DHJ, Tannenbaum T, Farrellee M, Livny M (2008) Inter-operating grids through delegated matchmaking. Sci Program 16:233–253
28. de Assunção MD, Buyya R (2009) Performance analysis of allocation policies for interGrid resource provisioning. Inf Softw Technol 51:42–55
29. de Assunção MD, Buyya R, Venugopal S (2008) InterGrid: a case for internetworking islands of Grids. Concurrency Comput: PractEx 20(8):997–1024
30. Riedel M (2009) Interoperation of world-wide production e-Science infrastructures. Concurrency Comput: Pract Ex 21:961–990
31. Grid Interoperability Now Community Group (GN-CG) (2009); Available at: http://forge.gridforum.org/sf/projects/gin, Accessed on: December
32. Quan DM, Altmann J (2009) Resource allocation algorithm for the light communication Grid-based workflows within an SLA context. Int J Parallel, Emergent and Distrib Syst 24(1)
33. Quan DM, Altmann J (2007) Business model and the policy of mapping light communication grid-based workflow within the SLA Context. HPCC 2007, High Performance Computation Conference, Houston, USA
34. Quan DM, Altmann J (2009) Grid business models for brokers executing SLA-based workflows. In: Rajkumar Buyya, Kris Bubendorfer (eds) Market-oriented grid and utility computing. Wiley, New York, USA
35. Rienstra SA, Nijkamp P (1996) Lessons from private financing of transport infrastructure: Dutch infrastructure in the 19th century and European projects in the 20th century. Serie Research Memoranda 0013. VU University Amsterdam, Faculty of Economics, Business Administration and Econometrics
36. Chanzdavarkar A (1994) Infrastructure finance: issues, institutions, and policies. Policy Research Working Paper 1374. Background paper for World Development Report. The World Bank Office of the Vice President, Development Economics
37. Mor N, Sehrawat S (2006) Sources of infrastructure finance. Working Paper Series, Centre for Development Finance Institute for Financial Management and Research
38. Dailami M, Leipziger D (1998) Infrastructure project finance and capital flows: a new perspective. World Dev 26(7):1283–129
39. Barmouta A, Buyya R (2003) GridBank: A Grid accounting services architecture (GASA) for distributed systems sharing and integration. Workshop on Internet Computing and E-Commerce, International Parallel & Distributed Processing Symposium (IPDPS 2003), France

40. Liebau N, Darlagiannis V, Mauthe A, Steinmetz R (2005) Token-based accounting for P2P-Systems. Kommunikation in Verteilten Systemen KiVS
41. Hausheer D (2003) Towards a market managed peer-to-peer file sharing system using token-based accounting and distributed pricing. Institut für Technische Informatik und Kommunikationsnetze, ETH Zurich, TIK-Report 179, Version 1, Zurich, Switzerland
42. Anandasivam A, Neumann D, Weinhardt C (2007) Rightsizing of incentives for collaborative e-Science grid applications with TES. Bled eConference, Merging and Emerging Technologies, Processes, and Institutions, Bled, Slovenia
43. Wongrujira K, Seneviratne A (2005) Monetary incentives with reputation for virtual marketplace based P2P. CoNEXT 2005, Toulouse, France
44. Cohen J, Darlington J, Lee W (2008) Payment and negotiation for the next generation grid and Web. Concurrency Comput: Pract Ex 20:239–251
45. Vishnumurthy V, Chandrakumar S, Sirer E (2003) KARMA: a secure economic framework for peer-to-peer resource sharing. Workshop on Economics of Peer-to-Peer Systems
46. MMAPPS Consortium (2004) Market management of peer-to-peer services: introduction and overview. Version 2.5, EC FP5 Project IST-2001-34201
47. Altmann J, Courcoubetis C, Stamoulis GD, Dramitinos M, Rayna T, Risch M, Bannink C (2008) GridEcon—a market place for computing resources. GECON 2008, Workshop on Grid Economics and Business Models. Springer LNCS, Las Palmas, Spain
48. Wolski R, Plank JS, Brevik J, Bryan T (2001) Analyzing market-based resource allocation strategies for the computational Grid. Int J High Perform Comput Appl 15(3):258–281
49. Neumann, D (2007) Towards an open Grid market. Economic models and algorithms for grid systems, Kumulative Habilitationsschrift, Fakultät für Wirtschaftswissenschaften, University of Karlsruhe
50. Buyya R, Abramson D, Giddy J, Stockinger H (2002) Economic models for resource management and scheduling in grid computing. J Concurrency Comput: Pract Ex 14(13–15):1507–1542
51. Fokkema T, Nijkamp P (1994) The changing role of governments: the end of planning history? Int J Transport Econ 21 (2):127–145
52. World Bank (2005) Financing information and communication infrastructure needs in the developing world. World Bank Working Paper 65. Washington, DC, USA
53. EGEE (2009) Website, http://www.eu-egee.org, Accessed on: November 2009
54. DEISA (2009) Website, available at: http://www.deisa.eu, Accessed on: November 2009
55. GEANT (2009) Website, http://www.geant.net, Accessed on: November 2009
56. DFN (2009) Website, http://www.dfn.de, Accessed on: November 2009
57. TeraGrid (2009) Website, http://www.Teragrid.org, Accessed on: November 2009
58. NAREGI (2009) Website, http://www.naregi.org, Accessed on: November 2009
59. K*Grid (2009) Website, http://www.gridcenter.or.kr, Accessed on: November 2009
60. CANARIE (2009) Website, http://www.canarie.ca", Accessed on: November 2009
61. EELA (2009) Website, http://www.eu-eela.org, Accessed on: November 2009
62. BALTICGRID (2009) Website, http://www.balticgrid.org, Accessed on: November 2009
63. SEE-GRID (2009) Website, http://www.see-grid.org, Accessed on: November 2009